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Design Criteria for Rocket Exhaust Scrubbers

Air Pollution Technology, Inc, San Diego, Calif

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

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Solid Rocket Fuels	Hydrogen Fluoride	Stationary Sources	21I	
Combustion	Atomizing	Gas-atomizing	21B	13H
Exhaust Gases	Spraying		07A	
Scrubbers			14B	
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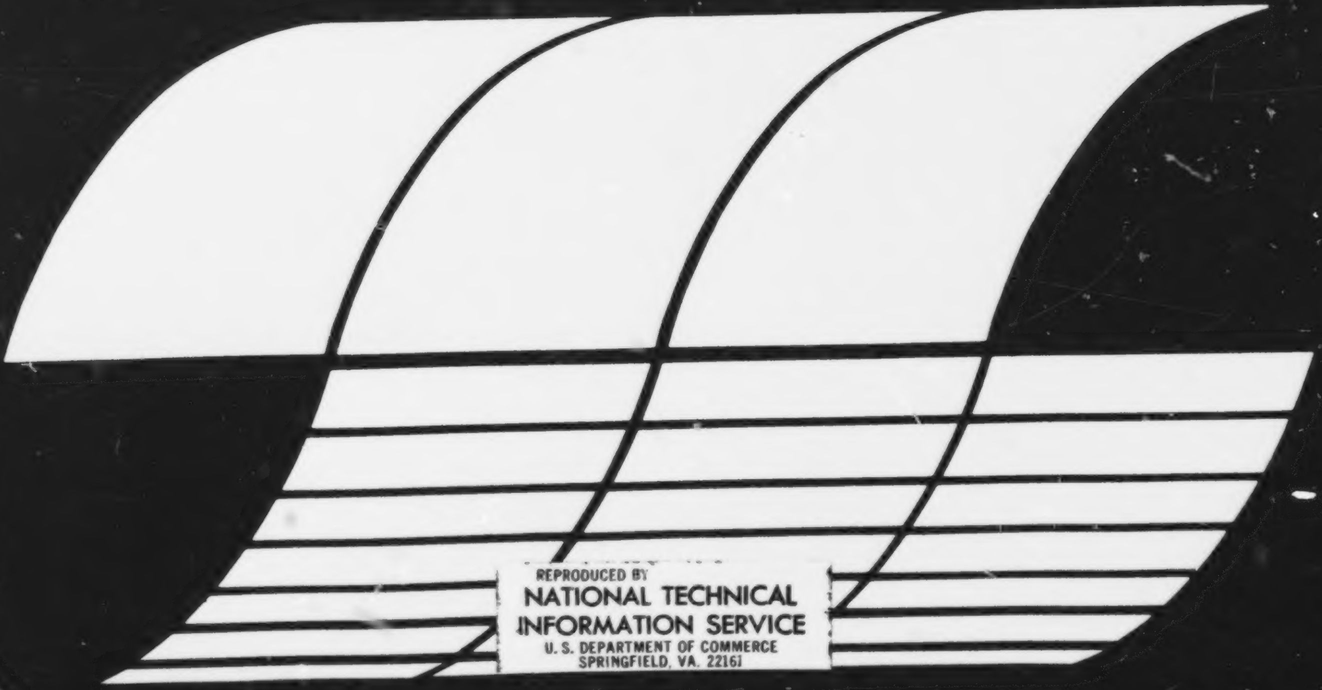

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by

Harry F. Barbarika and Seymour Calvert

Air Pollution Technology, Inc.
4901 Morena Boulevard, Suite 402
San Diego, California 92117

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U.S. AIR FORCE ROCKET PROPULSION LABORATORY
Edwards Air Force Base, CA
93523

ABSTRACT

An engineering study and design of methods of scrubbing the exhaust of experimental rocket propulsion systems have been performed. The study included an evaluation of the cost and technical feasibility of scrubbing the rocket exhausts. The exhaust products of major concern were hydrogen chloride and, to a lesser extent, hydrogen fluoride gases which result from the combustion of solid propellant rockets. The best process for removing these similar gases was found to be a gas-atomized spray scrubber which used the power supplied by the rocket to atomize the scrubbing liquid. Four tests in the 5,000 pound (22 kN) pilot scale rocket scrubber at the Air Force Rocket Propulsion Laboratory were analyzed to aid in the design. Two types of gas-atomized scrubbers were designed. One was a conventional design similar to a venturi; the other was a low-cost unconventional open type which did not use pressure piping nor a ducted spray chamber. Cost analyses were made for both types of scrubbers for rockets with thrusts between 4,500 pounds (20 kN) and 450,000 pounds (2 MN).

CONTENTS

Abstract iii
Figures. vi
Tables x
Abbreviations and Symbols. xii
  1. Introduction. 1
    Objectives 2
    Approach 2
    Requirements 3
  2. Background Information. 6
    Solid Propellant Rockets 6
    Supersonic Flow. 7
    Static Test Firings. 8
    Combustion of Solid Rocket Exhaust 9
    Flow Conditions of Solid Rocket Exhaust. 9
    Aluminum Oxide Particles 17
    Liquid Propellants 18
  3. Emission Reduction Objectives 20
    Required Efficiency. 20
    Constraints of Control Method. 21
  4. AFRPL Pilot Scrubber Tests. 22
    Introduction 22
    Solid Rocket Exhaust Conditions. 22
    Scrubber Design. 23
    Design Modification - Liquid Injection System. 26
    Instrumentation. 31
    Gas and Particulate Sampling 33
    Momentum Reduction Experiments 33
    Discussion of Tests. 36
    Conclusions from AFRPL Test Program. 58

CONTENTS (continued)

5. Air Pollution Control Equipment Alternatives 62
    Introduction 62
    Selection of Air Pollution Control Equipment . . . 62
    Equipment for Removal of HCl and HF 64
    Scrubbers Used on High Energy Exhausts 65
    Potentially Suitable Scrubbers 69
6. Detailed Design 71
    Definition of the Scrubbing Process 71
    Performance Requirements 96
    Conventional Scrubber Design 98
    Conventional Scrubber Entrainment Separation . . . 127
    Conventional Scrubber Costs 135
    Unconventional Scrubber Design 149
    Unconventional Scrubber Entrainment Separation . . 157
    Unconventional Scrubber Costs 164
    Scrubber Operation Costs 174
7. Conclusions and Recommendations 176

References 180
Appendices 184
    A. Programs for Calculating Quencher Equilibrium 184
    B. Conversions 197

FIGURES

Number		Page
1	Rocket exhaust flow rates.	12
2	Rocket exhaust power	15
3	AFRPL 22kN pilot scrubber.	24
4	Injector	27
5	Location of manometer probes and thermocouples	32
6	Sketch of location of thermocouples in entrainment separator section.	34
7	Location of filter holders in the entrainment separator exit	35
8	Test 1, rocket chamber pressure.	37
9	Test 1, scrubber duct wall temperature	37
10	Test 1, scrubbing liquid flow rate	38
11	Test 1, sampling pump vacuum pressure.	38
12	Photograph of AFRPL scrubber exit after test 1	39
13	Test 1, size distribution data	44
14	Test 2, rocket chamber pressure.	45
15	Test 2, scrubber duct wall temperature	45
16	Test 2, gas temperature in entrainment separator from thermocouple arrays.	46
17	Test 2, sampling pump vacuum pressure.	46
18	Test 2, velocity profile in scrubber	48
19	Photograph of liquid injectors after test 2.	50
20	Test 3, rocket chamber pressure.	51

FIGURES (continued)

Number Page

21 Test 3, scrubber duct wall temperature 51

22 Test 3, gas temperature in entrainment separator from thermocouple arrays. 52

23 Test 3, velocity profile in scrubber 52

24 Test 4, rocket chamber pressure. 54

25 Test 4, scrubber duct wall temperature 54

26 Test 4, gas temperature in entrainment separator from thermocouple arrays. 55

27 Test 4, pressure near rocket nozzle exit (diffuser inlet) 55

28 Test 4, velocity profile in scrubber 57

29 Schematic of rocket exhaust gas scrubbing process. . . 72

30 Comparison of velocity prediction with Garrett, et al. (1972) 80

31 Comparison of temperature prediction with Garrett, et al (1972). 80

32 Flow conditions in a closed quencher 83

33 Gas volume flow rate of 2 MN rocket closed quencher. . 83

34 Pressure rise in quencher. 84

35 Pressure rise versus thrust to duct area ratio 84

36 Concentration of HCl absorbed in quencher liquid . . . 85

37 Water vapor volume fraction. 85

38 Flow conditions in an open quencher. 89

39 Effect of entrained air on equilibrium velocity. . . . 94

40 Physical absorption of HCl 107

41 Liquid to gas ratio in scrubber. 109

FIGURES (continued)

Number Page

42 Effect of gas velocity on plume length required for HCl mass transfer to scrubbing liquor at 0.9 atm. . . 116

43 Rocket thrust coefficient 120

44 Sketch of gas-atomized scrubber section 122

45 Cyclone with tangential gas inlet 132

46 Outline of module cost format 136

47 Quench duct installed costs 143

48 Atomized spray scrubber costs 143

49 Cyclone costs 144

50 Water storage tank costs. 144

51 Caustic slurry supply pump costs. 145

52 Caustic storage tank costs. 145

53 Pipeline costs. 146

54 Quench and scrubbing liquor pump costs for small rocket scrubbers. 146

55 Drainage sewer costs. 147

56 Drying bed costs. 147

57 Total installed costs for conventional scrubbers. . . 148

58 Schematic of non-conventional rocket exhaust gas scrubbing process 151

59 Plan view of non-conventional scrubbing system. . . . 152

60 Typical cross-section of a non-conventional absorber configuration alternative 153

61 Sketch showing arrangement of tube bank separator . . 163

62 Transition piece costs. 169

63 Scrubber excavation costs 169

FIGURES (continued)

Number Page

64 Costs for scrubber excavation retaining walls, gunite, drag and deflector units for large rockets . . 170

65 Entrainment separator costs. 170

66 Scrubbing liquor viaduct and manifold costs. 171

67 Water storage tank costs 171

68 Caustic storage tank costs 172

69 Drainage sewer costs 172

70 Drying bed costs 173

71 Total installed costs for unconventional scrubber compared with conventional design 173

TABLES

Number Page

1 Composition of solid rocket exhaust 10

2 Flow conditions of solid rocket exhaust - composite propellant. 13

3 Estimated extremes of the ratio of nozzle exit temperature to pressure 14

4 Enthalpies of rocket exhaust. 16

5 Composition of liquid propellant rocket exhaust : . . 19

6 Required removal efficiencies 20

7 Composition of test rocket exhaust. 23

8 Predicted AFRPL test rocket flow conditions 23

9 Parameters for comparison with Garrett (1972) 79

10 Parameters for 2 meganewton rocket quenching prediction. 82

11 Equilibrium quench composition. 86

12 Combustion properties of H_2 and CO in air at standard conditions. 88

13 Scrubber inlet conditions for preliminary sizing. . . 98

14 Empirical constants for equation 35 99

15 Comparison of scrubber diameters. 100

16 Capital cost estimates for large rocket scrubber. . . 102

17 Basic chemical costs, mid-1977. 104

18 Chemical solubilities 105

19 Gas conditions at scrubber outlet 127

20 List of processing units making up the total conventional scrubbing process. 138

TABLES (continued)

Number Page

21 Worked examples of atomized spray scrubber costs . . . 142

22 Equilibrium conditions in unconventional scrubber without baffles. 155

23 List of components making up the total unconventional scrubbing process - large rockets 165

24 Worked examples of non-conventional scrubber costs . . 168

25 Scrubber operation plan. 174

LIST OF SYMBOLS

Latin

a = speed of sound, m/s

a = cyclone dimension, figure 35

A = area, cm^2 or m^2

b = cyclone dimension, figure 35

c^* = characteristic exhaust velocity, m/s

C = mass concentration, fraction

C_F = thrust coefficient, dimensionless

C_P = specific heat at constant pressure, cal/g-°K

C_R = resistance coefficient, dimensionless

C_T = nozzle thrust coefficient, dimensionless

d = diameter, cm or m

d_p = particle diameter, μm, μmA, or cm

D = diameter, m

D_c = cyclone dimension, figure 35

D_e = cyclone dimension, figure 35

D_G = gas phase diffusivity, m^2/s

E_R = required efficiency, %

f = fraction

F = thrust, N

h = convective heat transfer coefficient, cal/s-cm^2-°K

h = cyclone dimension, figure 35

k = conductivity, cal/s-cm-°K

LIST OF SYMBOLS (continued)

Latin

k = mass transfer coefficient, kgmol/s-m^2-atm

K_G = overall mass transfer coefficient, kgmol/s-m^2-atm

L/G = liquid to gas volume ratio, ℓ/m^3 or m^3/m^3

m = mass flow rate, kg/s

M = mach number, dimensionless

M.W. = molecular weight, kg/kgmole

n = mole flow rate, kgmol/s

N = molar flux, kgmol/s-m^2

N_{OG} = number of overall mass transfer units

p = pressure, N/m^2 (Pa)

P = pressure, N/m^2 (Pa)

P_r = Prandtl number, dimensionless

q = heat flow rate, cal/s

Q = volume flow rate, m^2/s

R = gas constant, J/°K-kg

R = mass flow rate ratio, kg/kg

R_e = Reynolds number, dimensionless

S = cyclone dimension, figure 35

S_c = Schmidt number, dimensionless

t = thickness, cm

T = temperature, °K

u = velocity, m/s

x = mole fraction in liquid

y = mole fraction in gas

LIST OF SYMBOLS (continued)

Greek

γ = ratio of specific heats, dimensionless

Δh_f = enthalpy of formation per mole, J/kgmol

ε = expansion ratio

η = efficiency, fraction or %

θ = time, s

μ = viscosity, kg/m-s

ρ = density, kg/m^3 or g/cm^3

σ_g = geometric standard deviation

Subscripts

a = air

c = column

d = drop

D = drag, duct

e = exit

EL = emission limitation

f = mean of free stream and surface

g = gas

gc = geometric count mean

G = gas

in = inlet

L = liquid

o = stagnation

out = outlet

LIST OF SYMBOLS (continued)

Subscripts

p = pollutant
r = rocket, relative
R = required
T = total
u = universal
v = vapor
w = water
x = x-axis direction
y = y-axis direction
1 = upstream
2 = downstream

SECTION 1

INTRODUCTION

The Air Force Rocket Propulsion Laboratory (AFRPL) has been concerned about the environmental effect of their experimental rocket testing for a number of years. In recent years the various efforts undertaken to understand and develop technologies to reduce the effects have taken the form of engineering design studies, pilot scale scrubber tests with experimental liquid and solid rockets, modeling of the atmospheric diffusion and dispersion of exhaust plumes, and analyses of HCl concentrations in exhaust clouds and at ground level. The goal of the engineering design studies has been to determine the technical and economic feasibility of scrubbing rocket motor exhausts. The primary exhaust products of interest being the particulate - Al_2O_3, and the gases - CO, HCl, and HF, which result from experimental rocket tests.

This report describes the rocket exhaust scrubber system design effort which has been performed under a U.S. Environmental Protection Agency (EPA) contract but was instigated by the AFRPL through an interagency agreement. The objective of the program has been to define the technology, feasibility, and cost for reducing the gaseous and particulate emissions from rocket firings so that a decision can be made as to what level of atmospheric pollution reduction is attainable and feasible.

The exhaust scrubber system design program began with a joint program by the AFRPL and the Arnold Engineering Development Center (AEDC) at Tullahoma, Tennessee. The result was the 5,000 pound (22 kN) thrust rocket exhaust scrubber system installed at AFRPL. A number of liquid and solid rockets were tested in this pilot facility. This report contains an analysis of the four solid rocket tests conducted.

The first phase of the present design effort was also performed by Air Pollution Technology, Inc. (A.P.T.) under an EPA contract, no. 68-02-1328. The results of this first phase study to determine what systems might be applicable to cleaning the exhaust from test firings of solid rockets were published in the report by Calvert and Stalberg (1975).

OBJECTIVES

The technical objective of the project has been to prepare design criteria for scrubbing systems to handle the exhaust from solid rocket motors ranging in thrust from 5,000 pounds (22 kN) to 450,000 pounds (2 MN). The design criteria include tradeoffs of scalability, cost, scrubbing efficiency, feasibility, and availability of equipment. The criteria also include definition of the processes involved in quantitative terms. Such important design specifications as flow rates of coolants, neutralizing agents, power and fuel requirements, treatment of the scrubbing media and coupling effects between scrubber and rocket are considered. The development of design criteria has been aided by testing in the AFRPL pilot scrubber.

APPROACH

The approach to accomplishing the objectives of the program has been to develop design criteria for the largest rocket, 450,000 pounds (2 MN) expected to be tested. The expected performance of the large rocket has been used as the process baseline for the design criteria. The largest rocket presented the most severe design problems and also caused the most pollution. In developing the design criteria special care was taken to present equations, data, graphs, etc. that can be used also for designing smaller scale scrubbers.

Because cost estimates based on conventional designs have reached exorbitant levels, design criteria for an unconventional type of scrubber as well as a conventional type have been developed. The unconventional design represents the least expensive design that could feasibly scrub the rocket exhaust. This design is a higher risk (i.e., possibly less efficient) since it has not been tested.

REQUIREMENTS

Specific requirements for the research were set forth in the contract under the "Scope of Work". The work to be accomplished was defined as:

> *The contractor shall assist the EPA in carrying out Phase II of Interagency Agreement EPA-IAG-R5-0644 by preparing design criteria for scrubbing systems to handle the exhaust from solid rocket motors ranging in thrust from 5,000 pounds to 450,000 pounds.*

The "Scope of Work" listed seven tasks that were used as guidelines and requirements for preparing the design criteria:

1. *The tradeoffs of scalability, cost, scrubbing, efficiency, feasibility and availability of equipment shall be considered in selecting the system components. The contractor shall generate the information necessary to support their selections.*

2. *The contractor shall determine the flow rates for neutralizing solutions and system cooling. The strength of the neutralizing agent used for removing the pollutants from the exhaust products shall be given as a percentage of the total neutralizing solution.*

3. *The contractor shall make an estimate of the amount of electrical power required for operation of the motors, pumps, precipitators, etc., used in the system.*

4. *The contractor shall make an estimate of the quantity and type of fuel that may be required for any burners.*

5. *The contractor shall evaluate and recommend the treatment requirements for the scrubbing media, and any resultant by-products, and its ultimate disposal process to meet ground water disposal standards and/or satisfy Class I disposal requirements.*

6. *The Air Force Rocket Propulsion Laboratory (AFRPL) will, within the limits of their system (5,000 lb thrust rocket exhaust scrubber) and with any minor modification required, perform specific tests or series of tests requested by the contractor to obtain data which will aid the performance of this work.*

7. *The contractor shall study theoretically the coupling effects between the rocket motor and the scrubber system. The EPA will choose the exhaust scrubber coupling method which has the least effect on the thrust measurement of the rocket motor and minimizes the exhaust emissions. This recommendation shall also consider cost against efficiency.*

The "Statement of Work" also set forth other requirements:

8. *At the completion of all of the preceding work, the contractor shall make an oral presentation to the AFRPL to present their findings and recommendations. They shall present supporting data to define the choices of components and processes for the exhaust scrubber. The contractor shall present the basis for their scaling factors. If the existing AFRPL 5,000 lb thrust exhaust scrubber cannot demonstrate feasibility and scalability, the contractor shall present their recommendation for an intermediate system. The conceptual design of the intermediate system shall be detailed as to design cost estimate, data requirements, reasons for choice of the particulate thrust level capability of the facility, a preliminary construction cost estimate, the proposed test program and a time phases schedule for events from design start to completion of the required test program. The AFRPL will, from this presentation, make the decision as to whether design and build contracts will be required for the intermediate system (thrust level specified by the contractor).*

9. *The contractor shall provide a preliminary cost estimate for construction of the facility to be designed.*

SECTION 2

BACKGROUND INFORMATION

The background information needed to design a scrubber consists of a complete description of both the process producing the effluent and the effluent itself. This section includes a description of solid propellant rockets and their static testing. A brief discussion of supersonic flow is given since this type of flow is not usually encountered in industrial applications of scrubbers. Finally a description of the flow conditions and composition of the solid rocket exhaust is presented.

SOLID PROPELLANT ROCKETS

The characteristics and design of solid propellant rockets are presented in several standard textbooks. Among them are the texts of Sutton (1963) and Hill and Peterson (1965). The information presented in the following paragraphs was derived primarily from these two references.

The propellant of solid rocket engines is contained in the combustion chamber itself. The propellants burn on exposed surfaces to produce hot gases which produce a reactive force when expanded through the rocket nozzle. Most solid rocket propellants contain all the materials necessary for sustaining combustion.

Propellants are usually distinguished as being homogeneous or heterogeneous. Homogeneous propellants contain fuel and oxidant within the same molecule. Double-base propellants (nitroglycerine-nitrocellulose) with small amounts of other additives are the most common examples of homogeneous propellants.

Heterogeneous mixtures of oxidizing crystals in an organic fuel binder are called composite propellants. The most common oxidizer is ammonium perchlorate. The fuel or binder is usually an organic polymer such as a polybutadiene or a polyurethane. Fine aluminum powder is often used in propellants because of its high heat of reaction with oxygen and its relatively high density. Additives or special binders containing forms of fluorine have also been used to increase the energy of the propellant.

The most important performance characteristic of a rocket is the thrust. The following equation describes the three factors affecting the thrust:

$$F = m\ c^*\ C_T \tag{1}$$

where F = thrust, N
m = mass flow rate of propellant, kg/s
c^* = characteristic velocity, m/s
C_T = nozzle thrust coefficient

Mass flow rate is a primary factor which determines the magnitude of the thrust. The characteristic velocity is dependent upon combustion chamber properties, such as ratio of specific heats, molecular weight, and combustion stagnation temperature. High temperatures and low molecular weights produce high values of "c*". The thrust coefficient is a function of nozzle geometry only. The thrust coefficient is a maximum when the pressure in the exhaust plane of the nozzle is the same as the ambient pressure. Since the nozzle throat is choked, the flow in the rocket nozzle is supersonic, which allows pressures other than ambient to exist in the nozzle.

SUPERSONIC FLOW

Flow of gases at speeds greater than those at which small disturbances (waves) are propagated through a compressible fluid is called supersonic. The speed of these small disturbances is called the speed of sound, a, which, in an ideal gas, is:

$$a = \sqrt{\gamma R T} \tag{2}$$

where γ = ratio of specific heats
R = gas constant
T = static temperature

The Mach number, M, is the ratio of the fluid speed, u, to the speed of sound:

$$M = \frac{u}{a} \tag{3}$$

Supersonic flow in ducts has different characteristics than are normally encountered with subsonic flow. The primary difference is that pressures within a supersonic duct are not influenced by downstream disturbances since pressure waves cannot propagate upstream in supersonic flow. Thus, one can put any disturbance whatsoever downstream of the rocket nozzle exit without affecting the pressure in the rocket chamber or within the nozzle. This last statement must be qualified if the boundary layer thickness (which may be subsonic) is a significant factor of the throat diameter. It must also be recognized that supersonic flow represents a larger than normally encountered kinetic energy. This energy is manifested when one attempts to decelerate supersonic flow in a duct. For adiabatic flow without mass addition, a compression practically equal to the rocket chamber pressure is required for deceleration to normally encountered speeds.

STATIC TEST FIRINGS OF EXPERIMENTAL SYSTEMS

Experimental rockets are tested extensively in the evaluation process of research, experimental development, and occasionally, engineering development of weapon systems. One phase of the testing is the static firing, or firing while the rocket motor is held immobile. Overall performance of the rocket motor can be determined by monitoring the thrust, chamber pressure, and other variables. Combustion temperature is usually so high that it is not monitored directly. Nozzle performance at high altitudes is determined in special facilities capable of attaining low pressures. Because of the potential for uncontrolled combustion (explosion), the testing is conducted by remote control from a protected barricade or enclosure.

COMPOSITION OF SOLID ROCKET EXHAUST

The AFRPL tests solid rockets which use three different types of propellants. For purposes of design of air pollution control equipment the relatively high energy formulations of these propellants are used:

1. Conventional Composite
   a. Ammonium perchlorate with binder
   b. 21% by mass aluminum powder
2. Composite with Fluoride Additive
   a. Ammonium perchlorate with binder
   b. Fluoride additive
   c. 18% by mass aluminum powder
3. Double Base
   a. Nitrocellulose-nitroglycerine
   b. 19.5% by mass aluminum powder

The chemical compositions of these three main types of high energy propellants are given in Table 1. The listed compositions are based on thermochemical computer program predictions supplied by AFRPL. The table shows only those components which are a significant mole percent of the exhaust. Trace amounts of various compounds, elements, and radicals are also predicted.

FLOW CONDITIONS OF SOLID ROCKET EXHAUST

Of the three types of propellants listed in Table 1, the conventional composite type produces the most halogen acid gas. This gas, as will be discussed in detail in Section 3, is the one of primary concern. Because the composite propellant produces the most pollution of the three types, the flow conditions for it will be discussed in detail in the following paragraphs.

The AFRPL has supplied a thermochemical computer program prediction for the composite propellant rocket based on a

TABLE 1. COMPOSITION OF SOLID ROCKET EXHAUST

Propellant Type		Composite	Fluoride	Double Base
Component	M.W.	Mole %	Mole %	Mole %
CO	28	19.4	28.9	33.0
CO_2	44	1.4	1.2	0.5
HCl	36.5	17.1	3.1	0
HF	20	0	1.9	0
H_2	2	29.4	26.0	28.9
H_2O(gas)	18	12.6	5.8	2.5
N_2	28	8.7	23.8	25.1
Al_2O_3 (solid)	102	11.4	9.3	10.0

Compositions are based on thermochemical predictions at approximately 2,400°K and 101 kPa (14.7 lbf/in^2).

chamber stagnation pressure of 6.89 MPa (1,000 lbf/in^2) and a nozzle area expansion ratio of 10. A summary of the prediction is given in Table 2. Also included in the table are calculations of the molecular weight based on the composition listed in Table 1, and the exit stagnation (total) conditions based on a specific heat ratio of 1.15. The nozzle exit stagnation pressure and temperature are not usually the same as the chamber stagnation conditions because chemical reactions occur between the chamber and the nozzle exit. These exit conditions are needed to extrapolate to other nozzle expansion ratios.

Volume Flow Rate

Volume flow rate can be calculated from the ideal gas law:

$$Q = \frac{m_T \ f_g \ R_g \ T_e}{p_e} \tag{4}$$

where Q = volume flow rate, m^3/s
m_T = propellant mass flow rate, kg/s
f_g = mass fraction of gases in exhaust
R_g = gas constant for exhaust gases, J/kg-°K
T_e = exit temperature, °K
p_e = exit pressure, N/m^2 (Pa)

For a rocket using the composite propellant with a specific burning rate or mass flow rate a wide variety of volume flow rates are possible. This is because the exit temperature and pressure can vary widely, depending on the design of the nozzle. The nozzle is usually expanded to provide atmospheric exit pressures; but sometimes in the interests of economy it is underexpanded. The stagnation pressure, which also affects the exit conditions, can also vary widely. Table 3 presents an estimate of the extremes in ratio of the exit temperature to pressure, which directly affect the volume flow rate.

Based on these extremes in the factors affecting volume flow rate, Figure 1 has been drawn. This figure presents the actual

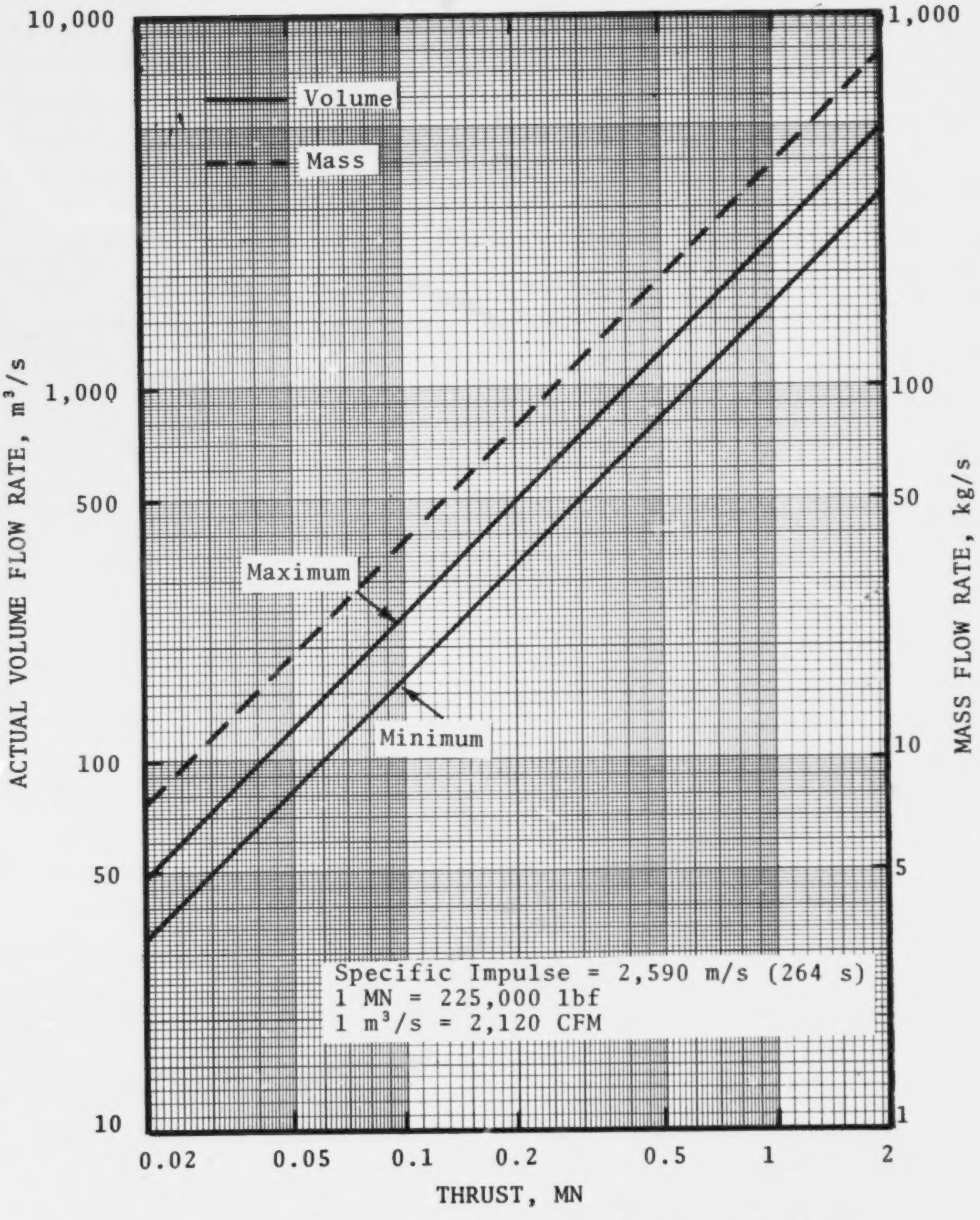


Figure 1. Rocket exhaust flow rates.

TABLE 2. FLOW CONDITIONS OF SOLID ROCKET EXHAUST - COMPOSITE PROPELLANT

	Metric	English
Assumptions:		
Chamber pressure	6.89 MPa	1,000 lbf/in^2
Nozzle Expansion ratio	10	
Predictions:		
Exit pressure	104 kPa	15 lbf/in^2
Exit temperature	2,400°K	4,320 °R
Specific impulse	2,590 m/s	264 s
Ratio of specific heats	1.15	
Chamber stagnation temperature	3,730°K	6,700°R
Based on composition listed in Table 1:		
Molecular weight of total exhaust	29.2	
Molecular weight of exhaust gases	19.8	
Gas constant of total exhaust	285 J/kg-°K	53.0 lbf-ft/lbm-°R
Gas constant of exhaust gases	412 J/kg-°K	76.6 lbf-ft/lbm-°R
Based on specific heat ratio of 1.15:		
Exit stagnation (total) pressure	7.23 MPa	1,050 lbf/in^2
Exit stagnation (total) temperature	4,170°K	7,510°R

TABLE 3. ESTIMATED EXTREMES OF THE RATIO OF NOZZLE EXIT TEMPERATURE TO PRESSURE

Stagnation Pressure kPa (lbf/in^2)	Exit Pressure kPa (lbf/in^2)	Exit Temperature °K(°R)	Ratio °K/kPa (°R/(lbf/in^2))
6,890 (1,000)	103 (15)	2,400 (4,320)	23.3 (288)
17,200 (2,500)	138 (20)	2,150 (3,780)	15.6 (189)

Stagnation temperature is assumed to be 4,170°K.

volume flow rate for the composite propellant as a function of the thrust level. Also shown is the total mass flow rate from the rocket based on the specific impulse of 2,590 m/s.

Enthalpy of the Rocket Exhaust

The ideal gas enthalpy and enthalpy of formation at 298°K for rocket exhaust gases can be found in Van Wylen & Sonntag (1973) and Section 3 of Perry & Chilton (1973). Table 4 presents some useful data from these references. For the composite propellant listed in Table 1 the static enthalpy at 2,400°K, relative to 298°K, is 96.0 kJ/gmol (22.9 kcal/gmol). The specific impulse is roughly equal to the exit velocity of the gas. A velocity of 2,590 m/s is equivalent to a dynamic enthalpy of 97.9 kJ/gmol (23.4 kcal/gmol) for a molecular weight of 29.2 g/gmol. The total enthalpy is thus almost equally divided between the heat and the kinetic energy of the rocket exhaust. The total enthalpy relative to 298°K (static) is the sum, 194 kJ/gmol (46.4 kcal/gmol). Figure 2 shows the total enthalpy rate (or power) of rocket exhausts for rockets of various thrusts based on the composite propellant.

Propellants Other than Composite Type

The properties of the exhaust flow of rockets containing propellants other than the high energy composite type are not significantly different. For precise estimates of the volume and energy flow rates one must follow the procedure used in the preceding paragraphs.

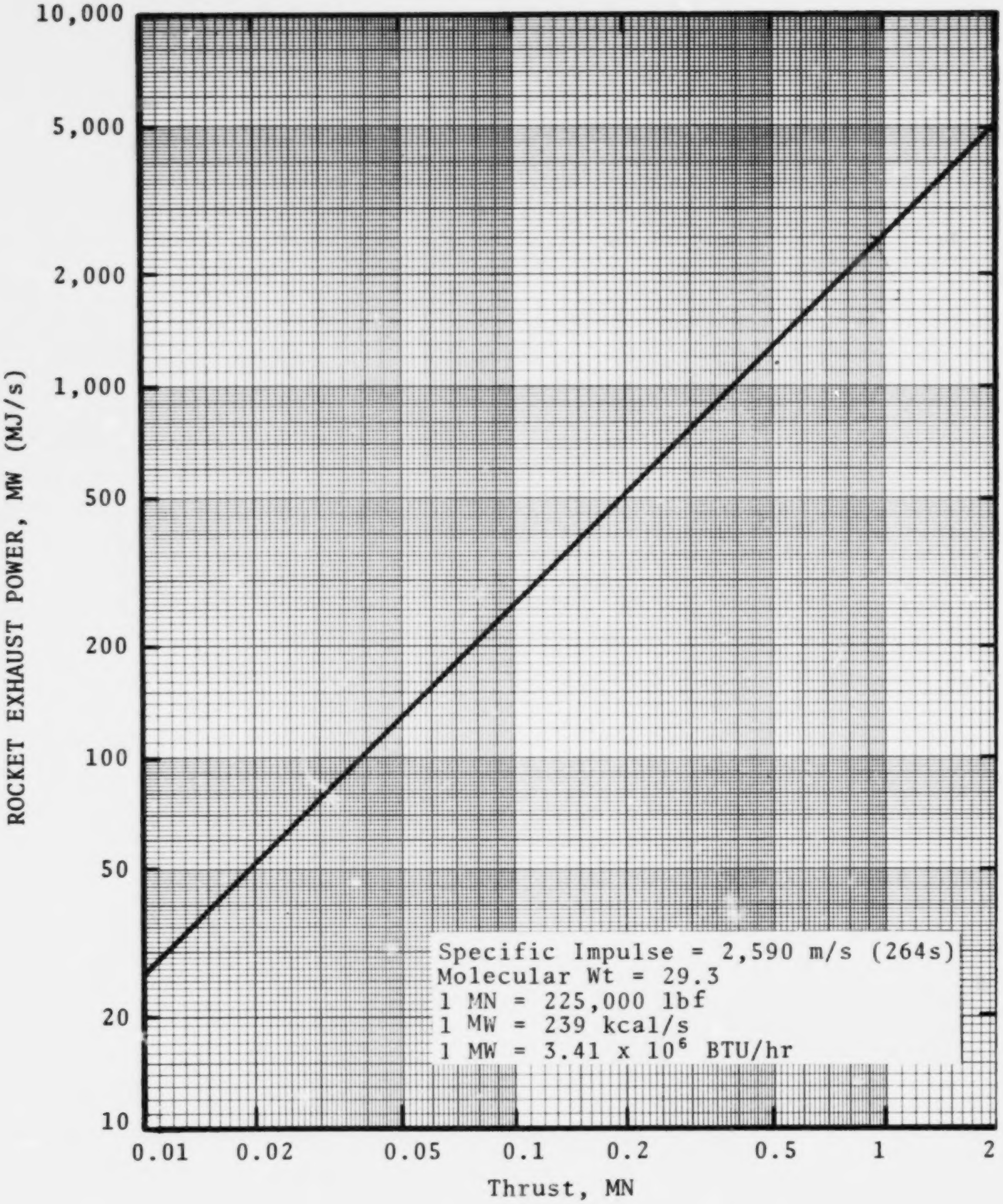


Figure 2. Rocket exhaust power.

TABLE 4. ENTHALPIES OF ROCKET EXHAUST COMPONENTS

Enthalpy of Formation at 298°K

Component	kJ/gmol	kcal/gmol
CO	- 110.5	- 26.417
CO_2	- 393.5	- 94.054
H_2O	- 241.8	- 57.798
$H_2O(1)$	- 308.3	- 73.678
HCl	- 92.3	- 22.060
HF	- 268.6	- 64.20
$Al_2O_3(s)$	-1,610.	-384.84

Ideal Gas Enthalpy at 2,400°K, Relative to 298°K

Component	kJ/gmol	kcal/gmol
CO	71.35	17.052
CO_2	115.8	27.674
H_2O	93.60	22.372
HCl	69.*	16.5*
HF	69.*	16.5*
$Al_2O_3(s)$	272.8	65.210
N_2	70.65	16.886
H_2	66.91	15.993
O_2	74.49	17.804

*Estimated

ALUMINUM OXIDE PARTICLES

While the total amount of the solid aluminum oxide particles produced was presented in Table 1, their size distribution was not. Data on size distributions of aluminum oxide as well as the adsorptive characteristics related to hydrogen chloride and hydrogen fluoride will be discussed in this subsection.

Size Distribution

Various techniques have been used to acquire data on aluminum oxide particle size from solid rocket firings. Prior to 1970 most techniques were biased to the larger sizes because they were based on the settling of particles in dishes downstream of the rocket nozzle. The collected particles were then analyzed by electron or optical microscopy. A summary of these data is given in Radke et al. (1967). These data have been correlated by Philco-Ford into the following equation based on throat size:

$$\begin{aligned} d_{pg} = {} & 1.439 + 6.2403 \times 10^{-1} D - 3.0535 \times 10^{-3} D^2 \\ & - 4.278 \times 10^{-4} D^3 + 8.6194 \times 10^{-6} D^4 \\ & - 4.634 \times 10^{-8} D^5 \end{aligned} \quad (5)$$

where d_{pg} = particle mean mass diameter, μm
D = throat diameter, inches (cm/2.54)

The standard deviation of the polynomial is 0.9 μm and the relation is not reliable over a throat diameter of 226 cm (89.1 in) or below a throat diameter of 2.4 cm (0.945 in). This correlation demonstrates that small rockets produce smaller average size particles than do larger rockets.

The standard deviations of the particle size distributions are not well characterized. However, Radke et al. (1967) present data for a rocket with a throat diameter of 31 cm (12 in) which has a geometric standard deviation of about 1.7 about a geometric mass mean diameter of 6.9 μm.

In recent years emphasis has been placed on submicron particles. Nadler (1976) reports that recent investigators have found that solid rocket motors produce a bimodal distribution of alumina. One distribution peaks in the submicron region and the other somewhere between 1 and 20 μm. Since most of the mass would be represented by the upper mode, the above equation (5) probably still represents the mass distribution. If number or surface area distributions were important the smaller mode would be important. Strand and Varsi (1974) and others working for the National Aeronautics and Space Administration (NASA) and Eisel et al. (1974) working for the Navy have been taking fine particulate data from solid rocket exhausts.

Adsorption of HCl/HF

Nadler (1976) has performed experiments to determine the amound of HCl adsorbed on alumina from rocket exhausts. He found that a small amount (6.7 percent by weight) of the total HCl produced could be adsorbed on the Al_2O_3 in a typical rocket exhaust. Similar small amounts of HF adsorption are also likely.

LIQUID PROPELLANTS

Although the main emphasis of this report is the solid rocket, the liquid propellant rocket should be mentioned. The exhaust products vary widely because the formulations vary. The products may be very similar to those of solid rockets, except for the aluminum oxide particulates. The primary exhaust products are shown in Table 5 for two typical liquid propellants. The hydrogen fluoride is produced in higher percentages by the F_2- H_2 liquid rocket than are either hydrogen fluoride or hydrogen cloride in most solid rockets.

TABLE 5. COMPOSITION OF LIQUID PROPELLANT ROCKET EXHAUST

Propellant Type:		F_2 - H_2	N_2O_4 - AZ - 50
Component	M.W.	Mole %	Mole %
CO	28		3.6
CO_2	44		3.8
HF	20	77.9	
H_2	2	22.1	22.6
H_2O (gas)	18		39.9
N_2	28		30.1

Reference: Garrett, et al. (1972)

SECTION 3

EMISSION REDUCTION OBJECTIVES

As of mid-1977, because of the intermittent and unusual nature of experimental rocket testing, the local air pollution control districts (APCD) had not specified any emission limits. There had previously been some activity in a local APCD to set some emission limits for rocket testing. These limits were 400 parts per million by volume of hydrogen fluoride (HF) and 800 parts per million of hydrogen chloride (HCl). None of the other exhaust products listed in Tables 1 and 5 were of concern. Because the scrubber design required an emission limit objective these limits on HF and HCl emissions have been used.

REQUIRED EFFICIENCY

The required removal efficiency of HF and HCl based on the composition of the rocket exhaust gas given in Table 1 is presented in the following table (6):

TABLE 6. REQUIRED REMOVAL EFFICIENCIES

Propellant Type	HCl Vol.%	HF Vol.%	Required Efficiency,%
Composite	19.3	0	99.6 (HCl)
Fluoride Composite	3.4	2.1	97.7 (HCl) 98.1 (HF)
Double Base	0	0	0

Volume percent as given in Table 6 is different than mole percent in Table 1 since the aluminum oxide particles do not occupy a significant volume. The required efficiency was calculated from the following equation:

$$\eta_R = \left(1 - \frac{f_{EL}}{f_p}\right) \times 100 \qquad (6)$$

where:

η_R = required efficiency, %
f_{EL} = fraction (or %) by volume emission limitation
f_p = fraction (or %) by volume of pollutant in effluent gas

Particulate removal was not required under present rules. However, because of the gas-liquid contacting required to remove the HCl and HF gases a high percentage of particulates will also be removed. Calculations of predicted particle removal efficiency, which will be presented later in this report, show that for many rockets, removal of enough HCl to meet emission limits will also result in removal of 99.9% by mass of the particulates.

CONSTRAINTS ON CONTROL METHOD

Since removal of large volumes of gas is required, it is likely that an absorber type control device will be used. Gas absorbers usually use water as the absorbing medium, which means that a supply of water will be required. The use of water is thought not to be a constraint because the use will be only intermittent.

Other possible physical constraints to be considered are topographical. Some test stands are situated on buttes and hillsides which require special design considerations.

SECTION 4

AFRPL PILOT SCRUBBER TESTS

INTRODUCTION

Part of the AFRPL program to reduce emissions resulting from experimental rocket testing activities was the evaluation of a pilot scale scrubber sized for a 22 kN (5,000 lbf) thrust rocket. These tests were conducted by AFRPL test personnel under the direction of the AFRPL project engineers, Mr. J. Hewes and Mr. L. Sedillo. The AFRPL made a limited but significant attempt to evaluate the pilot scrubber, however, inconclusive results were obtained because of sampling difficulties. This effort represented a significant commitment of resources. For reasons that will be presented later the project was terminated. The testing program has been reported by Sedillo (1978).

The testing program consisted of nineteen liquid propellant and four solid propellant tests. The initial test was conducted with liquid fluorine and gaseous hydrogen. An explosion of gases resulted in extensive damage to the demister section of the scrubber. After extensive modifications the pilot scrubber was tested eighteen times using nitrogen tetroxide and aerozine 50, a 50-50 mixture of unsymmetrical dimethylhydrazine and hydrazine. Many problems during this period plagued this project. This liquid rocket test was used to establish what modifications and improvements were required to satisfactorily test solid rocket motors.

The main concern of this section is the analyses of the four solid motor tests of 10 second durations conducted by the AFRPL.

SOLID ROCKET EXHAUST CONDITIONS

The propellant used in the tests was a composite type containing 14% aluminum by weight. The predicted exhaust composition is shown in Table 7 .

TABLE 7. COMPOSITION OF TEST ROCKET EXHAUST
(Composite, 14% Al by weight)

Component	M.W.	Mole %
CO	28	20.3
CO_2	44	3.6
HCl	36.5	16.8
H_2	2	23.5
H_2O (g)	18	20.3
N_2	28	8.5
Al_2O_3(s)	102	7.0

Total Molecular Weight = 27.0

Gas Molecular Weight = 21.4

Composition is based on AFRPL supplied thermochemical prediction at 2,100°K and 101 kPa (14.7 lbf/in^2).

Other predicted flow conditions are listed in Table 8.

TABLE 8. PREDICTED AFRPL TEST ROCKET FLOW CONDITIONS

	Metric	English
Thrust	22 kN	5,000 lbf
Specific Impulse	2,570 m/s	262 s
Mass Flow Rate	8.56 kg/s	18.9 lbm/s
Volume Flow Rate, actual	45 m^3/s	95,000 ACFM
Temperature, static	2,100°K	3,780°R

SCRUBBER DESIGN

The AFRPL pilot scrubber was a gas-atomized type, designed by ARO, Inc. of Arnold Air Force Station, Tennessee and reported in Garrett et al. (1972). A sketch of the scrubbing system is shown in Figure 3. The scrubbing duct was steel, 0.91 m (3 ft) in diameter and 9.1 m (30 ft) long.

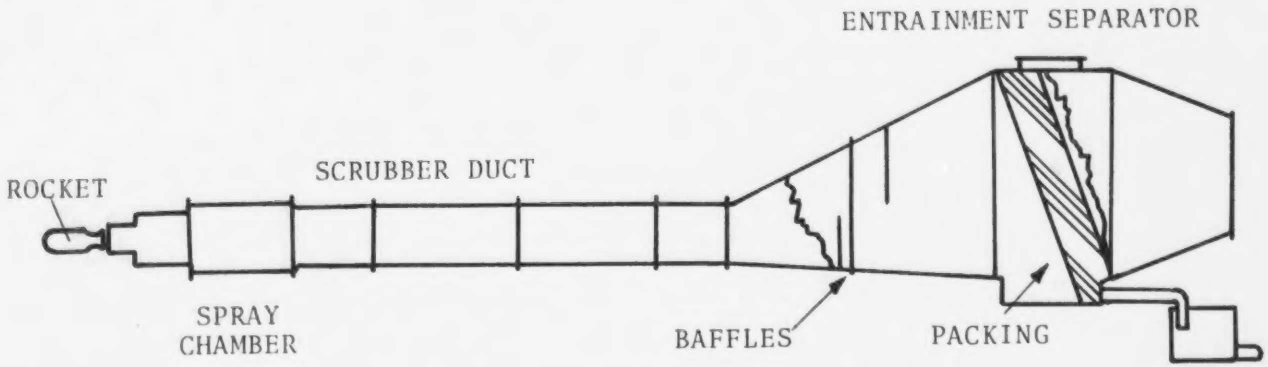

ENTRAINMENT SEPARATOR
ROCKET
SCRUBBER DUCT
SPRAY CHAMBER
BAFFLES
PACKING

Figure 3. AFRPL 22kN (5,000 lbf) pilot scrubber.

The mist eliminator section was made of fiberglass reinforced plastic and packed with 2.54 cm (1 inch) polypropylene Tellerettes® to a depth of about 0.61 m (2 ft). It was rectangular and inclined 70° from the horizontal. The mist eliminator was designed by the manufacturer (The Ceilcote Company, Berea, Ohio) for 45.5 m^3/s (120,000 CFM) and a total pressure drop of 0.75 kPa (3 in W.C.).

The outlet of the scrubber system was designed to facilitate sampling and was 2.13 m (7 ft) in diameter.

The liquid was supplied by a nitrogen gas pressurized spherical stainless steel tank with a 75.7 m^3 (20,000 gal) capacity. The liquid was a solution of potassium hydroxide (KOH). The effluent liquid was drained into an evaporation pond.

The inlet to the scrubber contained a cylindrical diffuser with a converging conical inlet to capture the rocket exhaust gases. The diffuser was intended to aid in collecting the lead and tail-off propellant gases by the aspirating action of the liquid spray nozzles. The lead gases were mainly those emitted during ignition of liquid propellants for which this pilot scrubber was also designed. Another function of the diffuser was to minimize blowback at tailoff. It was doubtful however that the diffuser had any effect on the scrubber operation other than to protect the rocket nozzle from splash of the injected scrubber liquor at startup and tailoff.

The diffuser did not reduce the flow to subsonic since the back pressure in the scrubber was not nearly great enough to cause a shock in the diffuser. The velocity at the diffuser exit was primarily governed by the area ratio between the diffuser to the rocket nozzle throat.

The scrubber liquid was injected through a number of radially situated jet nozzles. The nozzles were placed so that the liquid jets were directed inward to penetrate the rocket exhaust. Some of the jet nozzles were inclined downstream to provide some pumping action during startup and tailoff. The tips of the nozzles were outside the expected exhaust plume. The arrangement is shown in Garrett's report.

DESIGN MODIFICATION - LIQUID INJECTION SYSTEM

The only major design modification was a new liquid injection system. Since the supersonic exhaust flowing from the diffuser was expanded only to about atmospheric pressure, the plume retained its diameter for many diameters downstream. This column of supersonic, high temperature gas would be expected to melt any ordinary type of water injection nozzle located within it. Injection of water at the flow centerline was prerequisite to obtaining the maximum transfer of energy and momentum from the exhaust gases to the water. An injector that would not melt was one protected by a massive (high heat capacity) angle iron bar that was also cooled by jets of water from the injector.

The new injector design had three components:

1. A stainless steel pipe with holes drilled in the side to act as nozzles. The holes would be placed so as to inject water perpendicular to the flow from the diffuser and inject water toward the angle iron bar shield to help cool it.
2. An angle iron bar to shield the tube from the hot gases flowing from the diffuser.
3. A steel clamp to hold the shield on the tubing. A clamp is used because the shield may have to be replaced after one or more motor firings.

Figure 4 is a sketch of the injector. Three of these injectors were used in place of the old jet nozzles. Each spanned the full diameter of the spray chamber and intersected the centerline of the rocket exhaust. They were rotated 60° apart to fully cover the rocket exhaust.

In addition to providing a better means of injecting water into the center of the exhaust plume, the new design caused much greater mixing of the plume, the injected water, and the stagnant air.

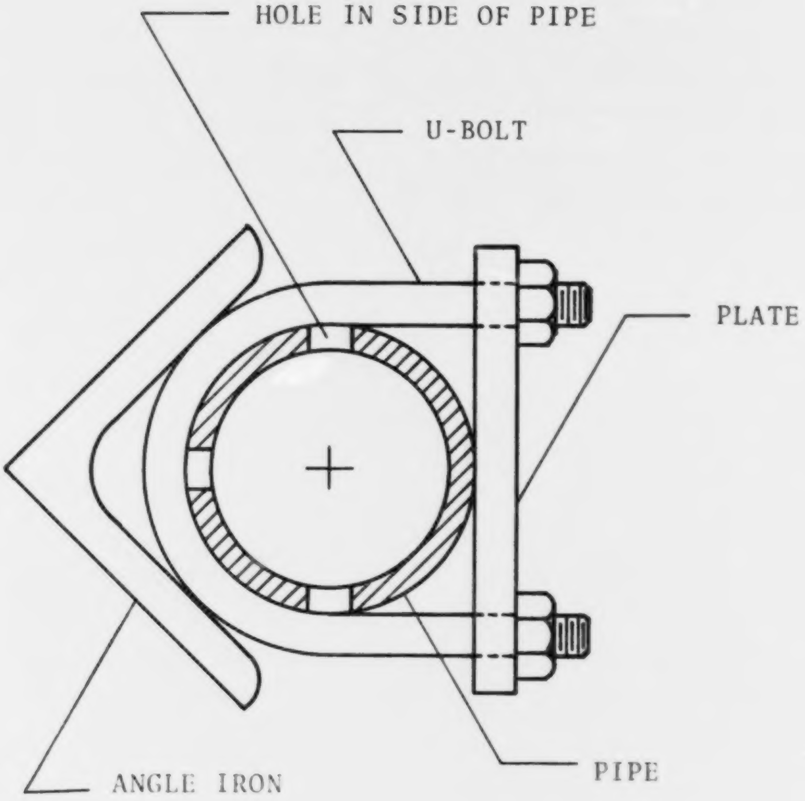

HOLE IN SIDE OF PIPE
U-BOLT
PLATE
ANGLE IRON
PIPE

Figure 4. Injector.

Heat Transfer Analysis of the Angle Iron Bars

The heat transfer to the angles which protect the water injection pipes in the new injector design was calculated. The analysis consisted of determining the flow condition, estimating the heat transfer coefficients, and performing calculations based on an idealized model.

The flow condition on the upstream side was assumed to be the condition that occurred just behind a normal shock in the rocket exhaust. The shock would be present because the supersonic rocket exhaust must slow down to stagnation at the tip of the angle iron. The flow on the downstream side contained mixed liquid-vapor due to boiling on the surface.

The convective heat transfer coefficient on the upstream side was estimated from analysis of forced convection over exterior surfaces (Holman, 1972, Chapter 6):

$$h_1 = \frac{0.246\ k_f}{d} \left(Re_{df}\right)^{0.588} \left(Pr_f\right)^{0.33} \qquad (7)$$

where "f" denotes that the property is evaluated at the arithmetic mean of the free stream and surface temperatures. For this case:

$$T_f = 2{,}500°K$$

and the following estimates are made:

Conductivity, $k_f = 4 \times 10^{-4}$ cal/s-cm-°C (0.1 BTU/hr-ft-°F)
Viscosity, $\mu_f = 6 \times 10^{-5}$ kg/m-s
Prandtl No., $Pr_f = 0.8$

The cross section diameter was:

$$d = 0.0718 \text{ m}$$

so, the Reynolds No., $Re_{df} = 323{,}000$

Substituting, the heat transfer coefficient is:

$$h_1 = 0.022 \text{ cal/s-cm}^2\text{-}^\circ\text{C} \ (160 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F})$$

On the downstream side the flow of water contains mixed liquid and vapor. According to Figure 10-14 in Kreith (1965) the most conservative heat transfer coefficient occurs at steam qualities between 50 and 100 percent, the coefficient at 100 percent being little different from the minimum.

The heat transfer coefficient is then (Kreith, 1965, Chapter 8):

$$h_2 = 0.023\, C_p\, \rho\, V \left(Re_{df}\right)^{-0.2} \left(Pr_f\right)^{-0.67} \qquad (8)$$

Here,

$T_f = 500^\circ K$

$C_p = 0.46$ cal/g-°C

$Pr_f = 0.95$

$d = 0.65$ cm

$\mu_f = 1.71 \times 10^{-5}$ kg/m-s

$\rho V = 494$ g/cm^2-s

So, $Re_{df} = 1.90 \times 10^6$

Thus, $h_2 = 0.30 \text{ cal/s-cm}^2\text{-}^\circ\text{C} \ (2{,}200 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F})$

The conductivity of steel at elevated temperatures is about:

$$k = 0.083 \text{ cal/s-cm-}^\circ\text{C} \ (20 \text{ BTU/hr-ft-}^\circ\text{F})$$

So that the heat transfer coefficient through the angle is:

$$h_A = \frac{k}{t} \tag{9}$$

$$= \frac{0.083}{t} \ \text{cal/s-cm}^2\text{-}^\circ\text{C} \quad (t \text{ in cm})$$

$$= \frac{20}{t} \ \text{BTU/hr-ft}^2\text{-}^\circ\text{F} \quad (t \text{ in cm})$$

The problem can be treated as a steady thermal resistance problem (Kreith, 1965, Chapter 1), with radiation neglected. The heat transfer per unit area is:

$$\frac{q}{A} = h_1\left(T_1 - T_{s_1}\right) = h_A\left(T_{s_1}\right) - T_{s_2} = h_2\left(T_{s_2} - T_2\right) \tag{10}$$

where the subscript "s" denotes the surface condition, and

q = heat flow rate, cal/s

A = area, cm^2

The results were that, considering only heat transfer, the thinner the better in this size range. The choice of the 0.64 cm (0.25 in) thickness was made as being convenient to use and stronger than the thinner angle. The average temperature of the 0.64 cm (0.25 in) angle was predicted to be 814°K (1,005°F) which means that, based on Sutton (1963), the strength of 302 stainless steel was 71 percent of its room temperature strength. The stainless steel would be preferred even though a slightly higher surface temperature would result due to the lower conductivity for stainless steel than was assumed in this analysis. The mild steel angle should hold up at the reduced strength because it is backed up by the pipe. Because the heat transfer is initially unsteady the time taken to reach steady state provides a safety factor. About eight seconds should be the time required for temperature buildup.

INSTRUMENTATION

The scrubber was instrumented to determine its performance characteristics. Pressure, temperature, and flow rates were monitored and 16 mm movie films taken.

Static Pressure (Refer to Figure 5)

1. Rocket Chamber - transducer
2. Diffuser Entrance - oil-filled manometer
3. Spray Chamber - oil-filled manometer
4. Scrubbing Duct - oil-filled manometer
5. Entrainment Separator - oil-filled manometer

The levels of the oil-filled manometers were recorded on 16 mm movie film.

Dynamic and Total Pressure

A rake across the flow field was located at the downstream end of the scrubbing duct to determine the velocity profile. On one side of the flow centerline there were ten impact (total) pressure tubes. On the other side there were three pairs of pitot-type tubes. The pressure probes were all connected to oil-filled manometers, which were filmed.

Liquid Pressure

Transducers were used to monitor the pressure of the liquid lines into the spray chamber.

Liquid Flow Rate

The flow rate of the liquid into the spray chamber was monitored by in-line flow meters.

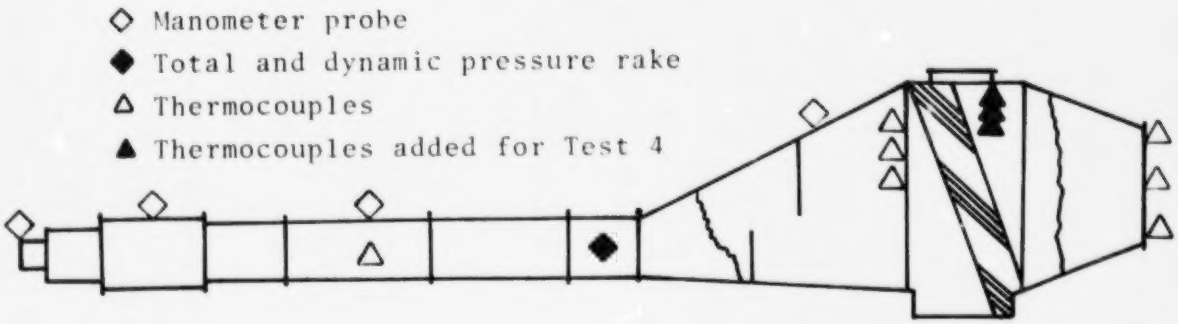

◇ Manometer probe
◆ Total and dynamic pressure rake
△ Thermocouples
▲ Thermocouples added for Test 4

Figure 5. Location of manometer probes and thermocouples.

Temperatures (Refer to Figures 5 and 6)

1. Scrubber Duct - thermocouples
2. Entrainment Separator - thermocouples
3. At Exit - thermocouples

It should be noted that thrust was not measured.

GAS AND PARTICULATE SAMPLING

The sampling system was located at the system exit. The gas sampling was done with evacuated 1-liter bottles. The probes were arranged on a support frame as shown in Figure 7. The sampled gas was analyzed by AFRPL using a mass spectrometer.

The system for collecting particles was designed by A.P.T. and consisted of an array of eighteen probes, precutter jars, plastic filter holders containing 47 mm Nuclepore^{R} filters at the system exit, and polyethylene tubing connected through a PVC pipe manifold to a Roots AF 22 blower. The blower was capable of pulling about 0.47 ℓ/s (1 CFM) through each of the 0.8 μm pore size filters. The suction through the filters was begun and stopped by switching the blower on and off at times corresponding to start and shut-down of the rocket motor. The probes were located just within the scrubber exit section. A 0-1 atm differential pressure transducer was placed on the inlet connection to the blower to monitor the blower inlet pressure (vacuum). The filters were returned to A.P.T. for gravimetric and optical sizing analysis.

MOMENTUM REDUCTION EXPERIMENTS

The original test plan called for eight 30-second duration tests, six of which would test momentum reducer plates. These plates were made but no tests were made. The principle behind the use of the plates was described in the Phase I report (Calvert and Stalberg, 1975). The purpose was to achieve a velocity reduction without having to expand the duct cross section or increase the amount of liquid required.

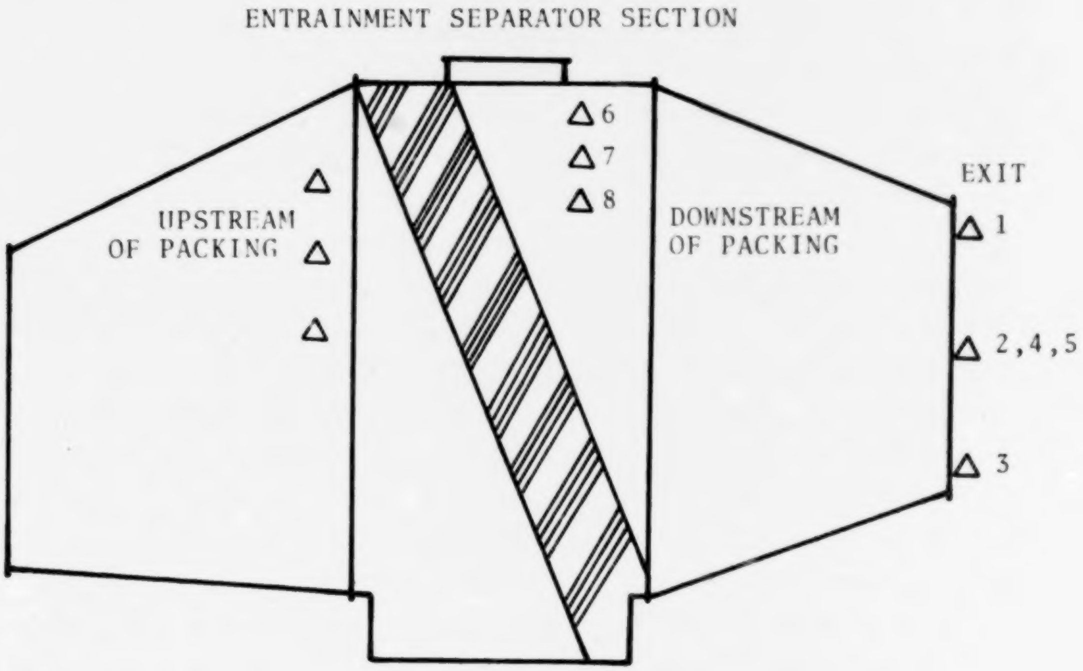
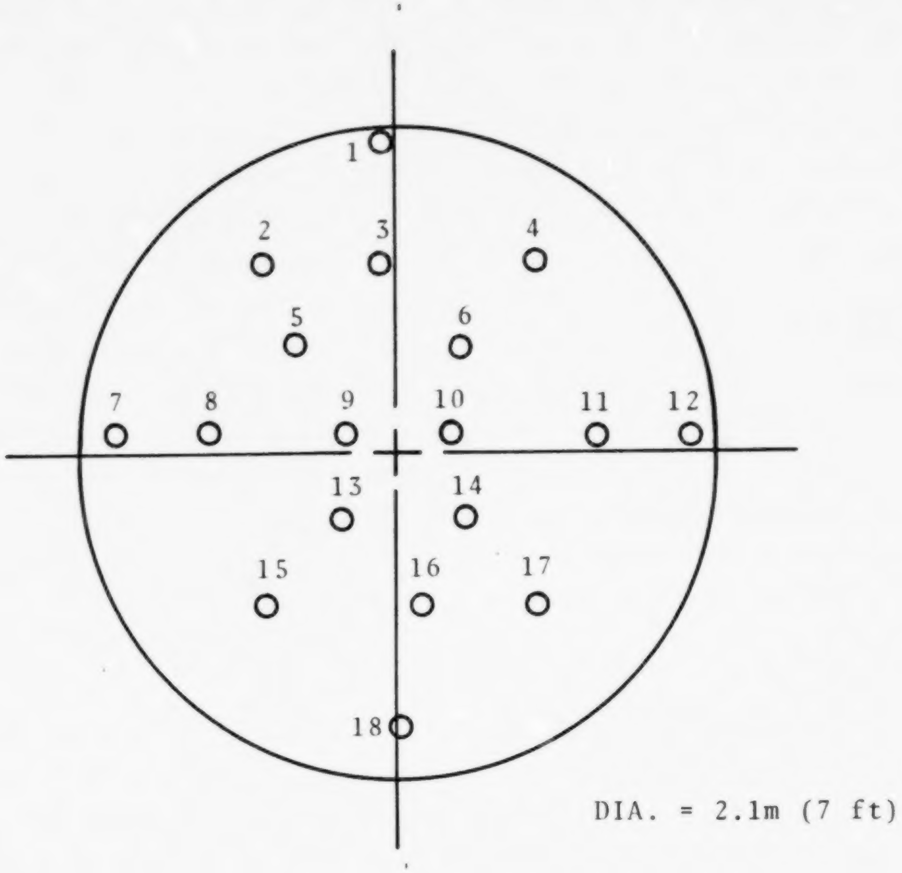

ENTRAINMENT SEPARATOR SECTION
UPSTREAM OF PACKING
6
7
8
DOWNSTREAM OF PACKING
EXIT
1
2,4,5
3

Figure 6. Sketch of location of thermocouples in entrainment separator section.


1
2
3
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18
DIA. = 2.1m (7 ft)

Figure 7. Location of filter holders in the entrainment separator exit.

The plates would act as scoops to collect drops, thereby reducing their forward momentum, and then reinject the drops into the stream to absorb extra exhaust momentum. The experiments were planned to test this design and a flat, inclined, design to determine if the reinjection was significant relative to the fluid drag of the plates.

DISCUSSION OF TESTS

Test No. 1 - October 8, 1975

On October 8, 1975 a 10 second duration solid rocket of 22,000 newton (5,000 lbf) nominal thrust was fired into the AFRPL pilot scrubber. The rocket performed as expected, but the cameras, set up to record manometer readings and to provide a visual record of what happened at the scrubber exit, did not function. Thus, no pressures were recorded that would indicate what the conditions were inside the scrubber. The most unexpected event was the melting and smoldering of the sampling apparatus set up at the exit of the scrubber. The polyethylene lines to the gas sampling bottles apparently melted through and let air into them. The plastic filter holders remained intact, although some were severely damaged. The amount of flow through them was not known since some of their polyethylene tubing also melted.

Test Data-

The recorded data are shown in Figures 8-11 . The scrubbing duct wall temperatures were less than 100°C as predicted. The scrubbing liquid flow rate was about 80 ℓ/s which is about 9.3 times the rocket mass flow rate.

Post Test Inspection-

The appearance of the apparatus after the test indicated that a flame or other high temperature producing phenomenon had been present. The effects can be seen in the post-test photo of the exit in Figure 12. The cameras, set up to provide a pictorial record of the test, did not operate, so it was not certain that a flame was present.

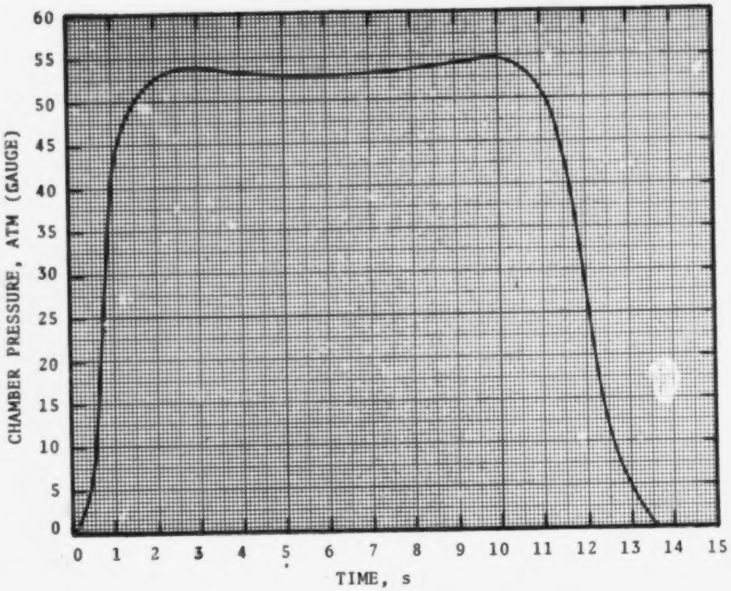


Figure 8. Test 1, rocket chamber pressure.

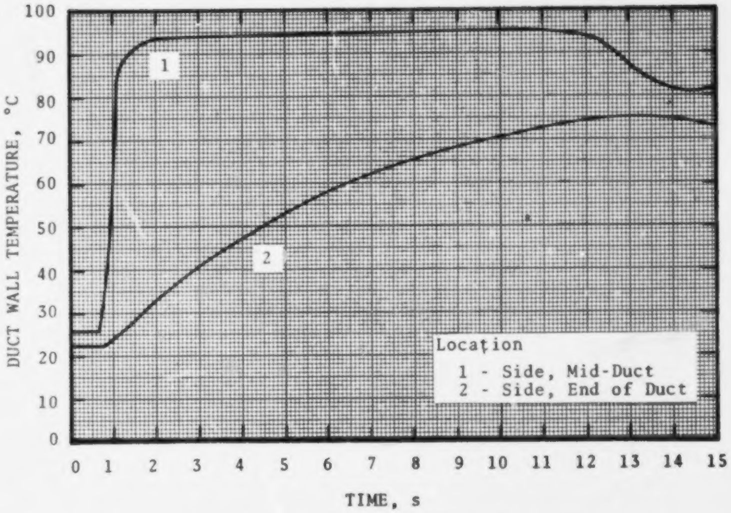


Figure 9. Test 1, scrubber duct wall temperature.

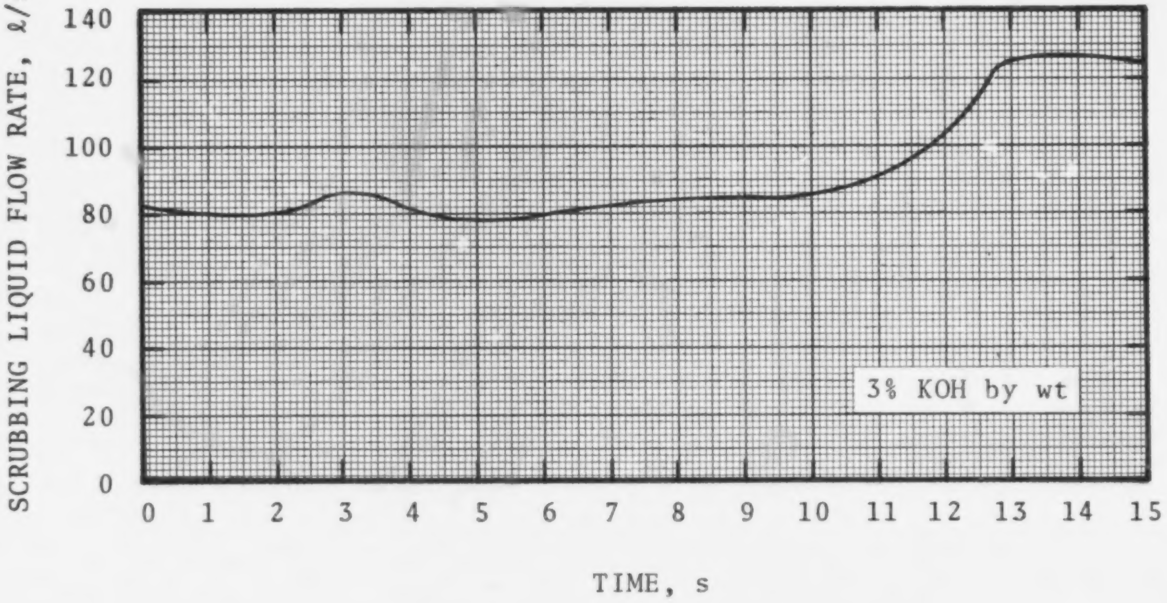


Figure 10. Test 1, scrubbing liquid flow rate.

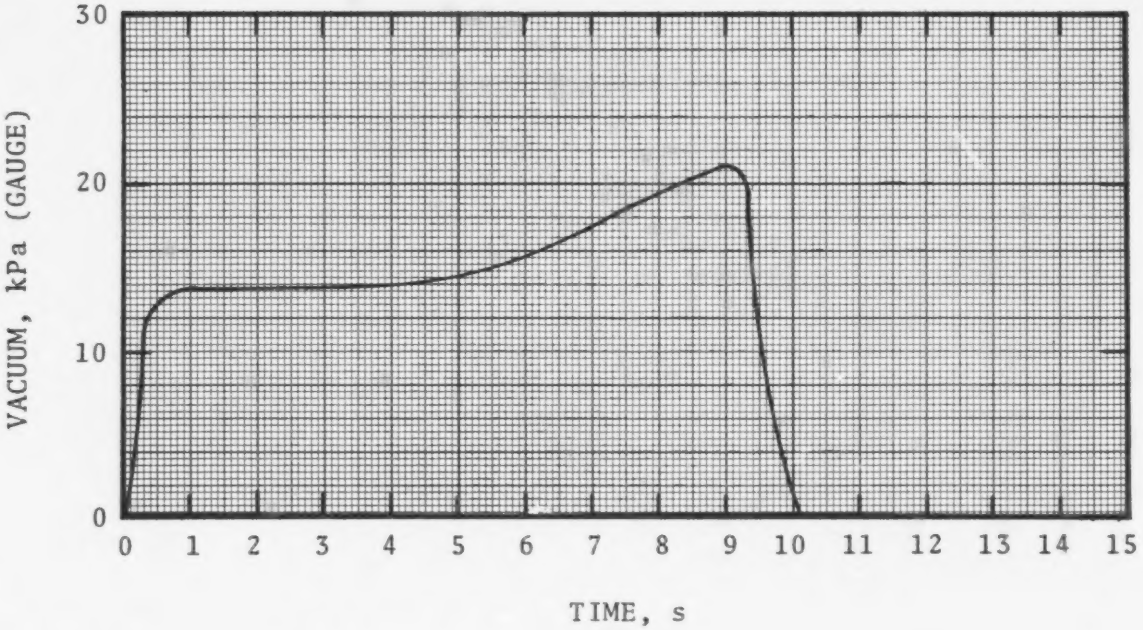


Figure 11. Test 1, sampling pump vacuum pressure.

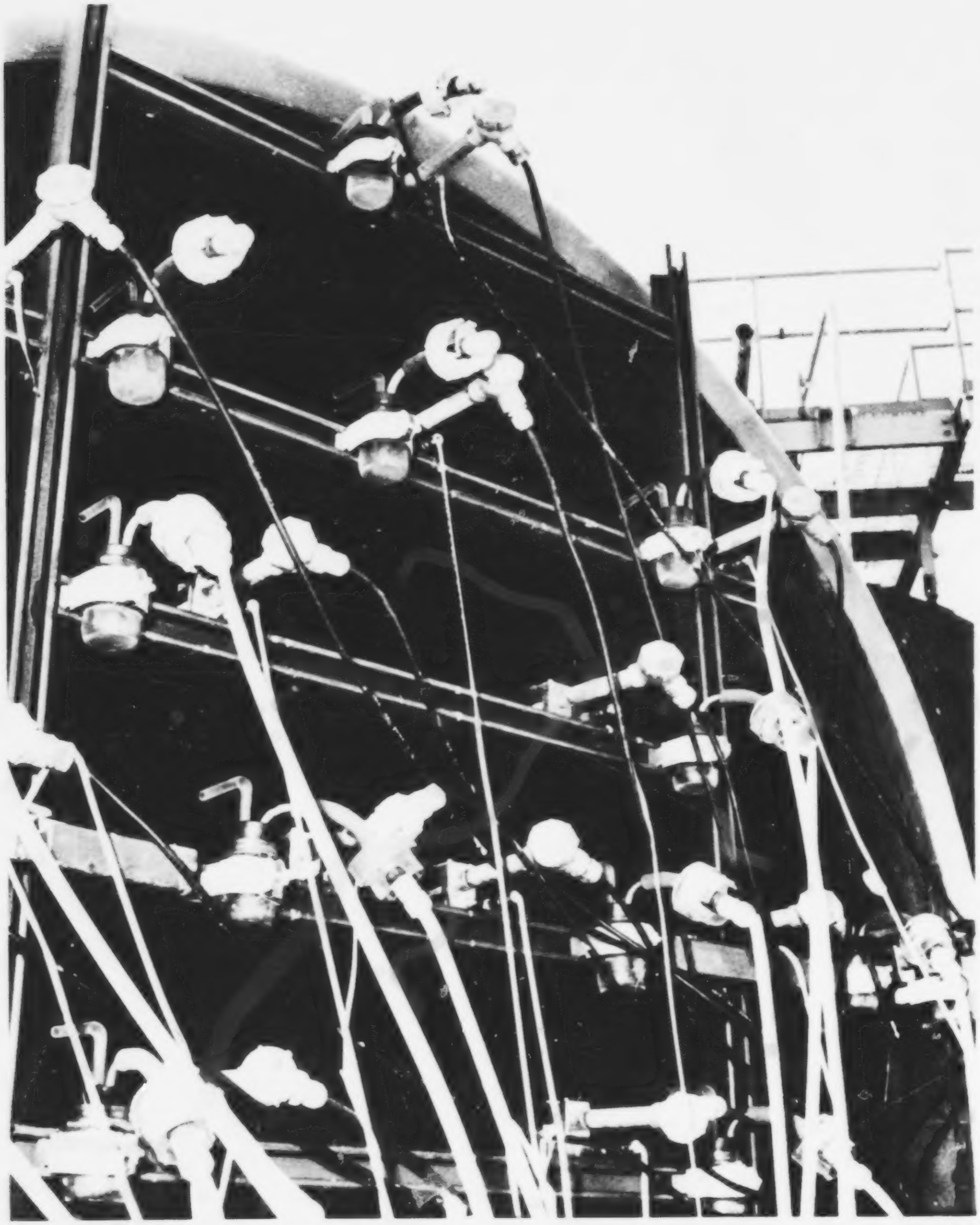


Figure 12. Photograph of AFRPL scrubber exit after test 1.

Heat effects were physically evident in the upper samplers. Numbers 1, 2, 3, and 4 in Figure 7 showed the greatest damage. On these samplers the following were observed:

1. The polyethylene tubing had melted through.
2. The polycarbonate plastic filter holders showed bubbling, melting, and charring.
3. The PVC reducing bushings were charred on one side.
4. The red rubber hose connections showed signs of melting on the outside and were sticky to the touch.
5. The gummed paper labels were charred.
6. The nylon tubing fittings were only very slightly charred.

To understand the causes of the damage to the apparatus the following data and observations were compiled:

1. The temperature of the gas should have been no higher than 95°C since that was the temperature measured upstream in the mixing duct, and equilibrium theory predicted a temperature of less than 100°C.
2. The exhaust of the solid rocket tested contains about 20 percent carbon monoxide and 2 percent free hydrogen (by weight).
3. High temperature effects were not observed for liquid rockets tested previously. The liquid rockets tested previously produce very little CO and H_2.
4. The pattern of severest temperature effect was at the top and along the outside of the scrubber outlet.
5. Nylon, polycarbonate, and polyethylene have maximum service temperatures in the range 120-150°C.
6. The Nuclepore® filters, made of polycarbonate plastic and with a maximum service temperature of 140°C, did not appear to be affected at all.
7. The polypropylene Tellerettes, used as packing in the demister, showed no high temperature effects.

The findings led to the conclusion that the most probable occurrence was combustion of carbon monoxide and hydrogen either during or just after the rocket firing.

Weight Gain of Filters -

The filters were weighed on a Cahn Model 4100 Electrobalance before and after the test. Although Nuclepore filters are non-hygroscopic they were kept in a desiccant jar and also baked at 80°C for a few hours prior to final weighing. The mean weight gain was 0.8 milligrams and the standard deviation was 0.3 mg. The largest gain (1.6 mg) was found on filters 4 and 10, and the least gain (0.5 mg) on filter 18 (see Figure 5).

The pore size of the Nuclepore filters was 0.8 μm diameter which means 100% retention efficiency for particles larger than 0.8 μm diameter and somewhat less efficiency for smaller particles.

Since some of the polyethylene tubes melted through, presumably while the blower was in operation, the particulate mass loading of the gas could only be estimated. If burning of the connecting tubing occurred after the end of the sampling period the nominal flow of 0.47 ℓ/s (1 CFM) for ten seconds would have passed through the filters and the mean particulate loading would have been about 5 mg/m^3 (actual). Converting to loading in terms of dry normal volume it would have been 40 mg/DNm^3, since the temperature was about 92°C and the moisture content was about 83% by volu[illegible] This represents a particulate collection efficiency of about 99.99% since the rocket produces a particulate (Al_2O_3) loading of about 0.4 kg/DNm^3.

Particle Size Analysis -

Several of the filters were examined using a Nikon model S-kt optical microscope. The filters were placed on slides and left uncovered during the examinations. Although illumination by transmitted light was available, the best illumination occurred using reflected light. Photo-micrographs, using a Polaroid attachment, were made of selected particles.

Most of the counting was done at 1500X with immersion oil directly on the Nuclepore filter. The sizing was accomplished by comparison with a Porton graticule incorporated in one of the oculars of the binocular eyepiece. The slide was moved randomly about the center of the filter until about 200 particles were counted. About 50 particles could be seen at each location. The smallest discernible particle corresponded to circle number 2 on the graticule, which was calibrated at 0.32 μm diameter. Most of the large particles (greater than 1 μm) observed were agglomerates. These agglomerates appeared to be made up of spheres about 0.6 μm to 0.8 μm diameter fused together. The agglomeration appeared to have occurred while the particles were very hot, and not on the filter. The results of two counts are given in Figure 13. As can be seen, the count mean diameter was around 1 μm.

Since immersion oil was used for viewing at 1,500 power, comparisons of refractive indices between the particles and the oil could be made. The particles had a higher refractive index than the immersion oil (1.515). This determination eliminates the possibility of potassium chloride (r.i.=1.49) and strengthens the probability that the particles are aluminum oxide (r.i. 1.70-1.77).

Comparison of Particle Size Distribution Reported in the Literature -

Recent investigations of rocket exhaust alumina have been reviewed briefly by Nadler (1976) as reported in Section 2. He found that the size distribution may be bimodal, with one peak in the submicron region and the other from about 1-20 μm. Small motors produce a smaller average particle size and a greater percentage of the gamma (γ) crystalline form of alumina, while larger motors produce a greater percentage of alpha (α) alumina. The rocket tested in this program had a throat diameter of 5 cm, which, according to data compiled by Radke, Delaney and Smith (1967) should produce a particle distribution with a mass mean diameter of about 2.7 μm. This size should correspond to the distribution peak in the large size region, although in rockets this small the peaks may not be far apart.

The data presented in Figure 13 for Test 1 show a geometric count mean diameter of about 1 μm and a "σ_g" of about 2.35. Converting to mass size distribution yields the value of 9 μm for the geometric mass mean diameter. This high result for the geometric mass mean diameter may be due to "d_{gc}" and "σ_g" values which are probably high because particles smaller than 0.3 μm could not be seen so that bias toward counting the larger particles existed.

It should also be remembered that the data shown here are for a sample taken after the scrubber, which should alter the size distribution considerably. The mean diameter should be lowered by the scrubber which is more efficient on the larger sizes. The scrubber could have, however, caused agglomeration.

Test No. 2 - February 27, 1976

A second 10-second duration test in the AFRPL pilot scale scrubber was made on February 27, 1976. The instrumentation and cameras performed successfully. The scrubber seemed to work except that, again, there was heat generated somewhere in the entrainment separator section. This heat generation was evident from thermocouple data and on the films. The films showed the polyethylene tubing, hung at the scrubber exit, actually burning in flames. Thermocouple data just upstream of the entrainment separator packing (Tellerettes) showed temperatures below 100°C. Another unexpected occurrence was the absence of a steam condensation plume out the scrubber exit. The only steam condensation cloud appeared on top of the entrainment separator section around the pressure relief hatches. The gas coming out the scrubber exit was very clear with no visible plume. Gas samples were not taken. The liquid (3% KOH) flow rate was about 100 ℓ/s.

Pressure and Temperature Data-

The pressure transducer and thermocouple data are shown in Figures 14-17. One side of the scrubbing duct was over-

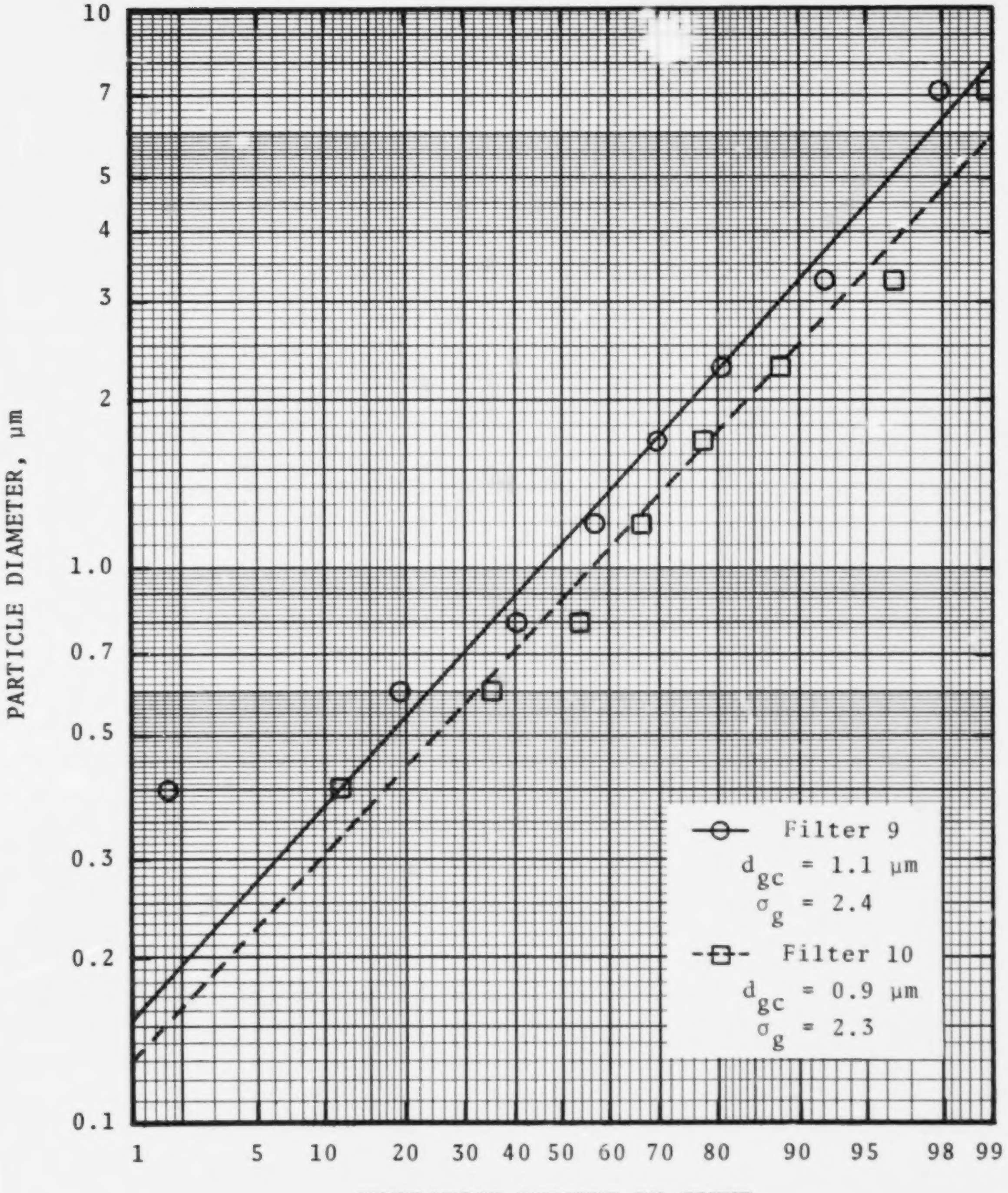


Figure 13. Test 1, size distribution data.

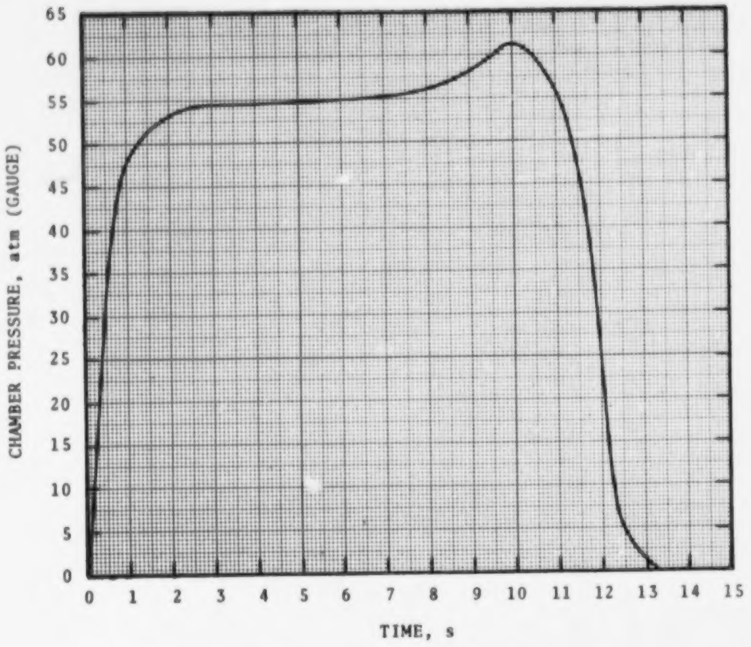


Figure 14. Test 2, rocket chamber pressure.

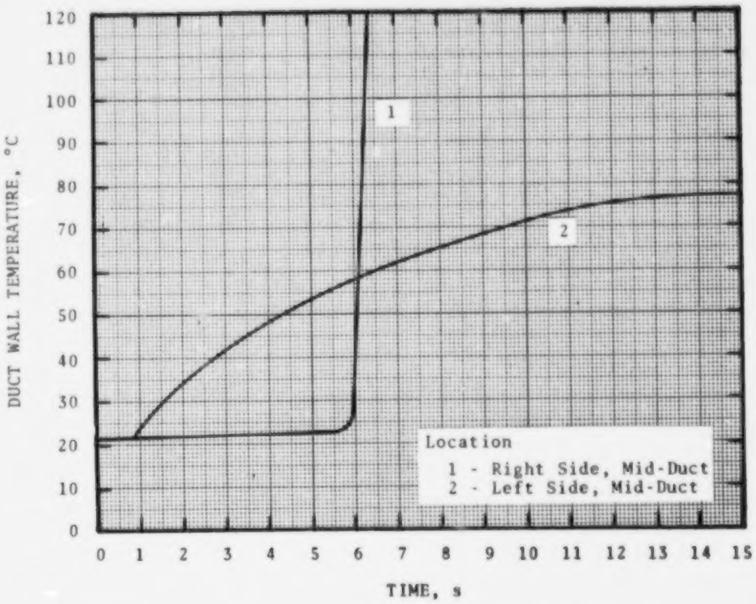


Figure 15. Test 2, scrubber duct wall temperature.

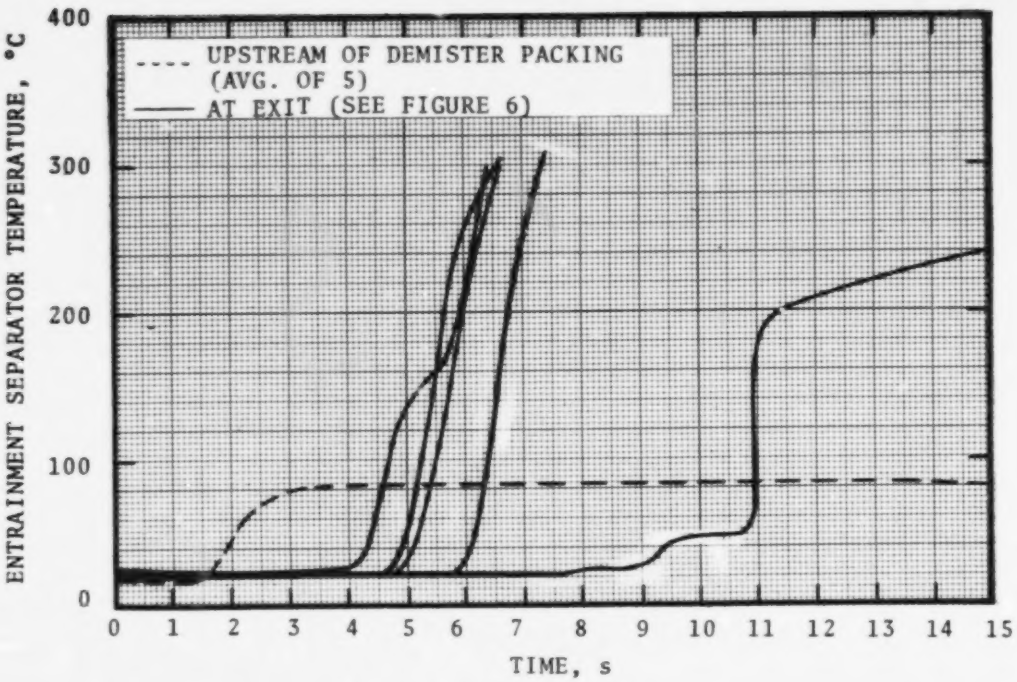


Figure 16. Test 2, gas temperature in entrainment separator from thermocouple arrays.

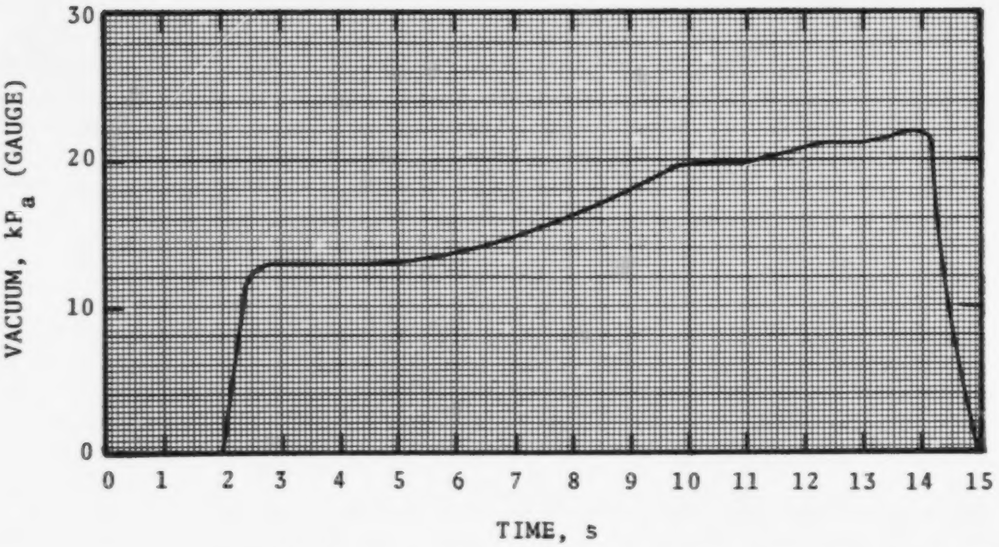


Figure 17. Test 2, sampling pump vacuum pressure.

heated, but this was due to improper arrangement of the liquid injection pipes, which allowed deflection to one side. This was later corrected. Arrays of thermocouples were placed in the entrainment separator section to quantify the effects of afterburning. From Figure 16 it is apparent that afterburning started about 4-5 seconds into the test firing and occurred only downstream of the demister packing. These high temperatures occurred mainly in the gas stream since the walls and packing were not significantly affected.

Velocity Profile at End of Scrubbing Duct-

One of the cameras filmed the manometer board to show the total, impact pressures across the scrubber at the end of the straight mixing chamber section. The pressure data are plotted in Figure 18, and show a fairly uniform velocity except at ±10% from the center. The maximum peak velocity is estimated to be about 200 m/s.

Particulate Data-

Nuclepore filter (0.8 μm pore diameter) samples of the exhaust were taken. For this test aluminum tubing was used instead of polyethylene tubing. The mean loading was 1.66 mg with a standard deviation of 0.78 mg. It was estimated that about 0.51 m^3 of gas went through the eighteen filters so that the loading was approximately 33 mg/m^3 at a temperature somewhere around 300°C. These loading data are very approximate because four of the filters had small visible holes due to melting, and the temperature was not known with any accuracy. Particle size distribution determinations were not made.

Chemical Analyses-

The entrainment separator packing and sump liquid were analyzed by AFRPL and the results were:

1. The surface of the Tellerettes was examined by scanning electron microscopy. A small quantity of particulate

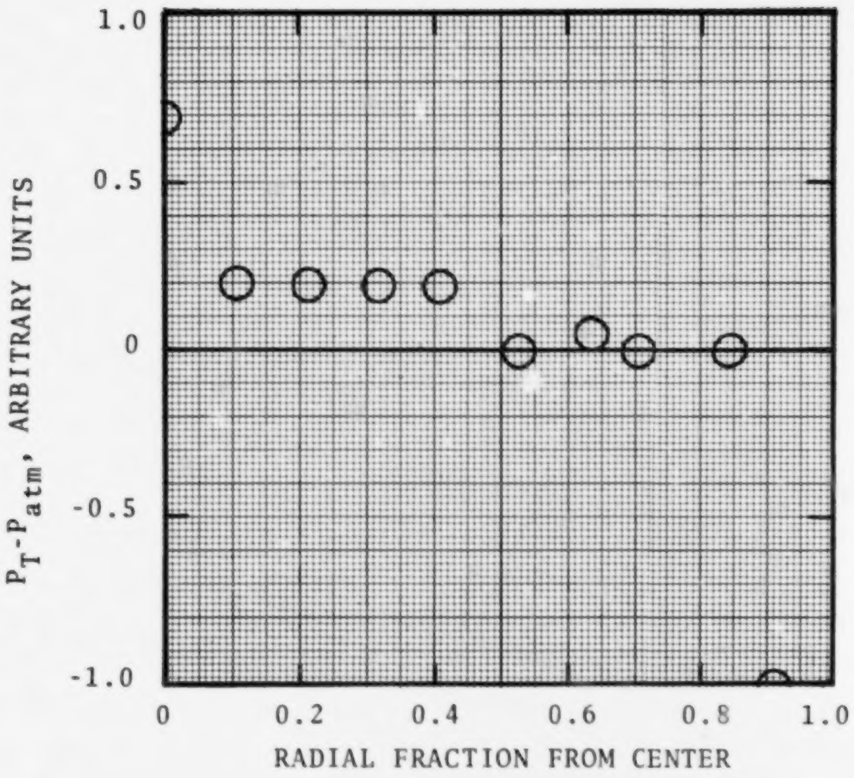


Figure 18. Test 2, velocity profile in scrubber.

matter was observed. Aluminum (Al or Al_2O_3) and silicon (sand) were the principal constituents. Traces of iron were also present.

2. The liquid phase of the demister sump sample contained high levels of potassium and lesser quantities of chloride and aluminum. The solids were primarily aluminum, probably aluminum oxide.

Performance of Liquid Injectors-

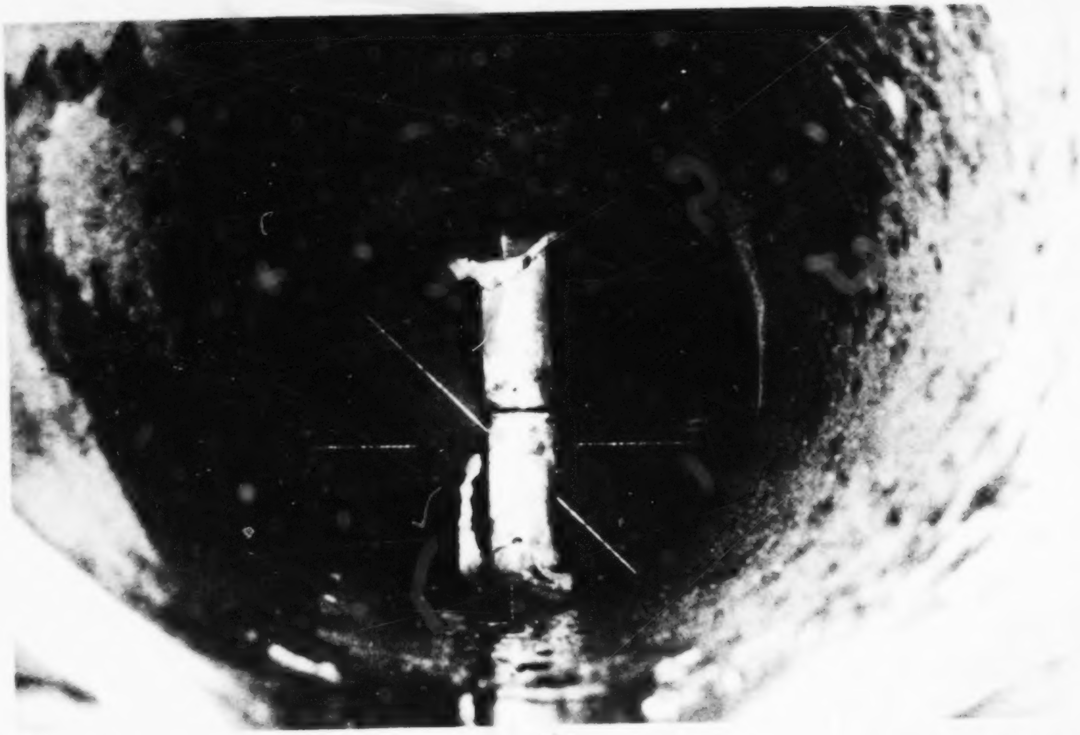
The liquid injector pipe/angle iron system was photographed after the test. One of the photographs is shown as Figure 19. Note that while the first angle iron burned off, the pipe was still intact. The second and third angle irons were not burned seriously. It was decided to provide more cooling to the angle iron of the first injector by drilling more holes in the pipe around the center of the duct.

Test No. 3 - November 5, 1976

A third 10-second duration test was conducted with water sprays on the entrainment separator packing. The sprays were an attempt to dilute and cool the gas to prevent afterburning downstream of the packing. A total flow rate of about 4 ℓ/s (66 GPM) of fresh water was used for the sprays. Neither gas samples nor particle samples were taken. Again 113 ℓ/s (1800 GPM) of a 3% KOH solution was used.

Pressure and Temperature Data-

The pressure transducer and thermocouple data are shown in Figures 20-22. Temperatures within the scrubber duct and upstream of the entrainment separator packing were less than 100°C as expected. Downstream of the packing the thermocouple data showed that some exit locations reached 650°C (1,200°F) during the firing. This was the first time the thermocouple scale used was that high. Previously, the readings had gone off the scale. Even though the thermocouple registered so



AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CA
NONRECORD MATERIAL

OFFICIAL USAF PHOTOGRAPH
BY: MR. RICHARD VAN-ETTEN

Figure 19. Photograph of liquid injectors after test 2.

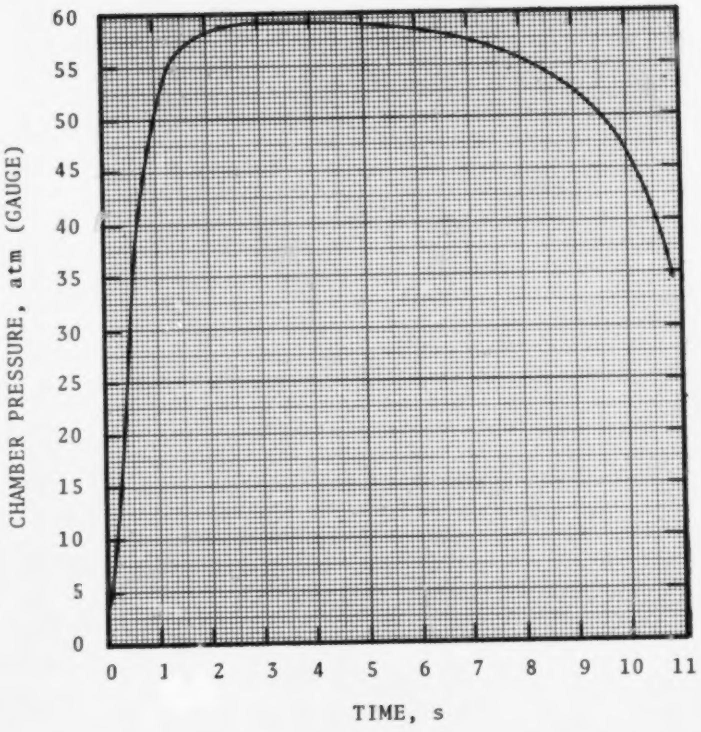


Figure 20 . Test 3, rocket chamber pressure.

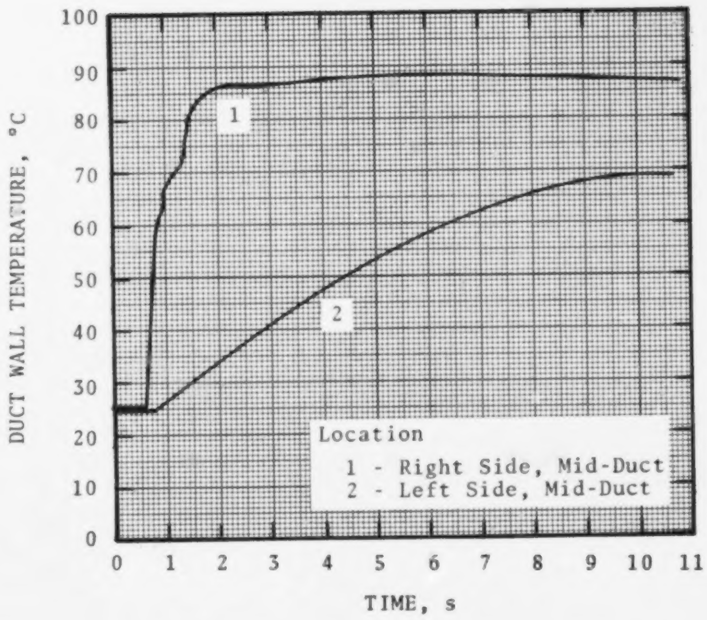


Figure 21 . Test 3, scrubber duct wall temperature.

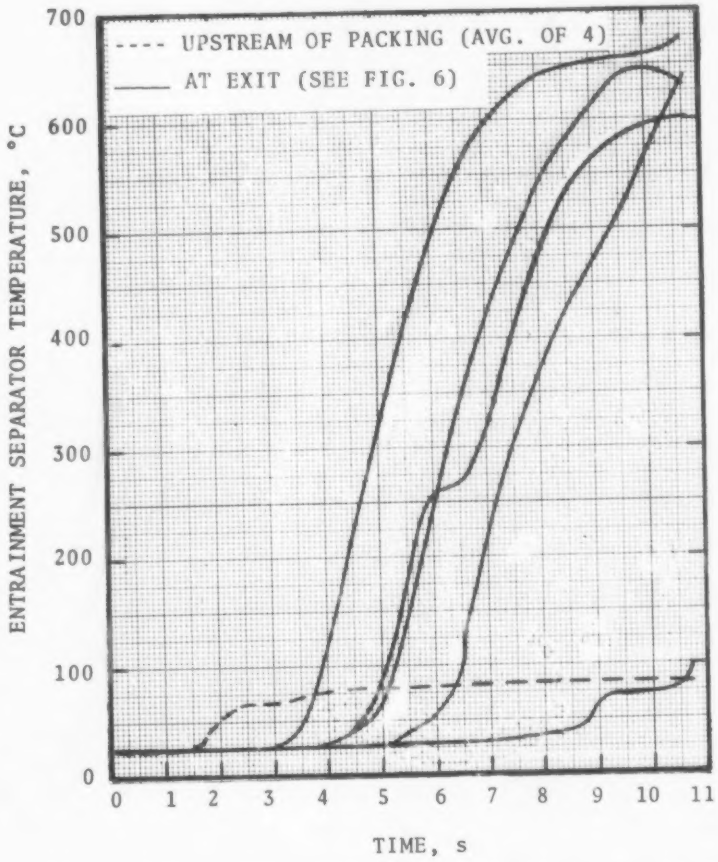


Figure 22 . Test 3, gas temperature in entrainment separator from thermocouple arrays.

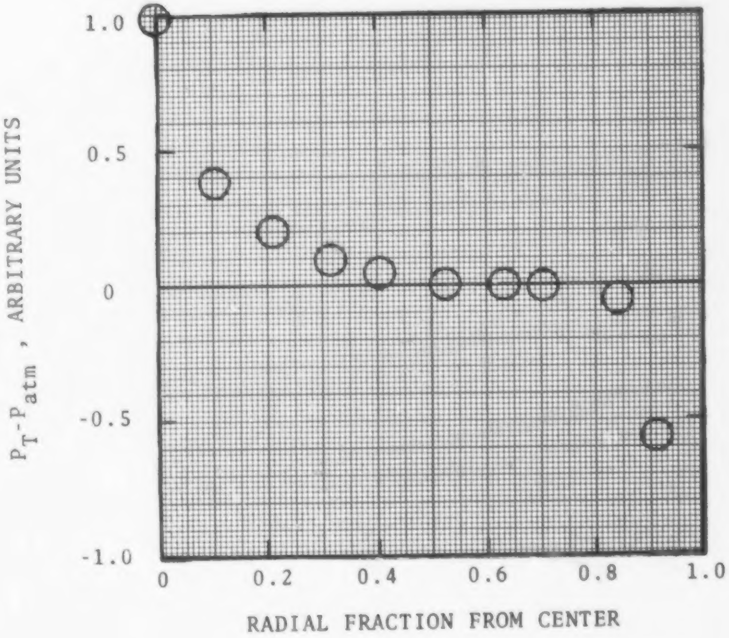


Figure 23. Test 3, velocity profile in scrubber.

high a temperature, the fiberglass structure housing the demister was not damaged. As with previous tests, the only damage within the system was to the polyethylene Tellerette packing and the fiberglass packing supports. These were melted slightly along the top of the demister. It was evident that the added sprays had no noticeable effect on the afterburning.

Velocity Profile at End of Scrubber Duct-

The total pressure relative to atmospheric at the end of the scrubber duct is shown in Figure 23. The profile is similar to that of the second test.

Performance of Liquid Injectors-

As in the previous test, the first angle iron shield for the liquid injection pipe burned through. The burned-out gap was narrower than the previous, only about 5 cm (2 in). The pipe itself was still intact, as were the other two angle iron and pipe injectors. More holes should be drilled in the first pipe, near the flow centerline, to try to get more heat transfer away from the center of the angle iron.

Test No. 4 - November 19, 1976

The final test in the series duplicated the conditions and results of the third test. One difference was an attempt to grab gas samples through tubes inserted into the entrainment separator section, just after the packing. Also, three thermocouples were inserted inside the entrainment separator section to monitor temperatures inside the section. Previous downstream temperatures were measured at the exit.

Pressure and Temperature Data-

The pressure transducer and thermocouple data are shown in Figure 24-26. It is important to note that the temperature at the exit (thermocouples 1 and 2) reached 650-850°C while those inside, just after the packing (thermocouples 6, 7, and

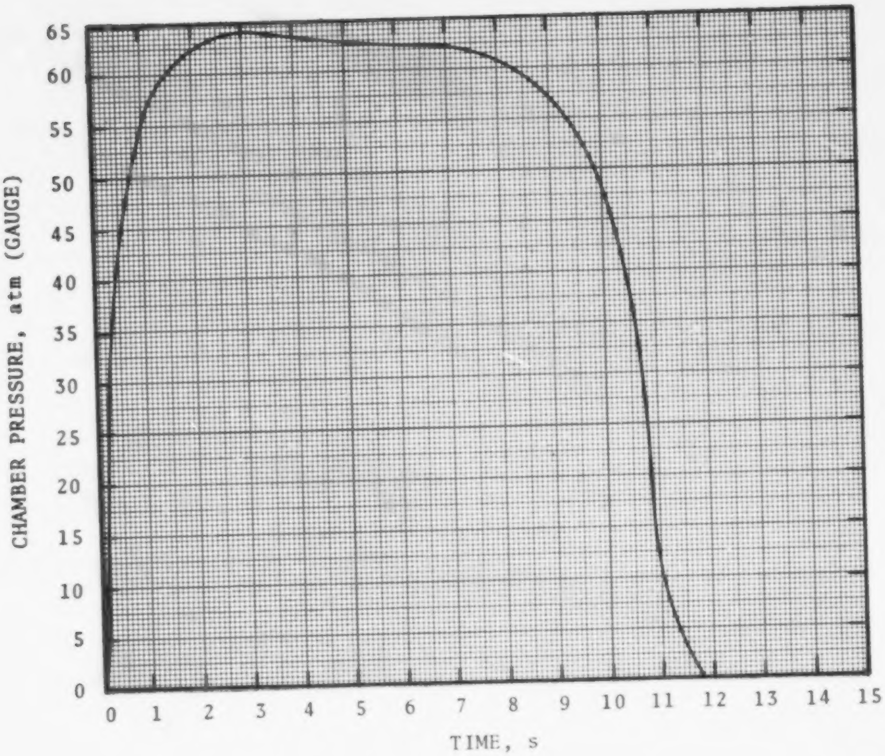


Figure 24. Test 4, rocket chamber pressure.

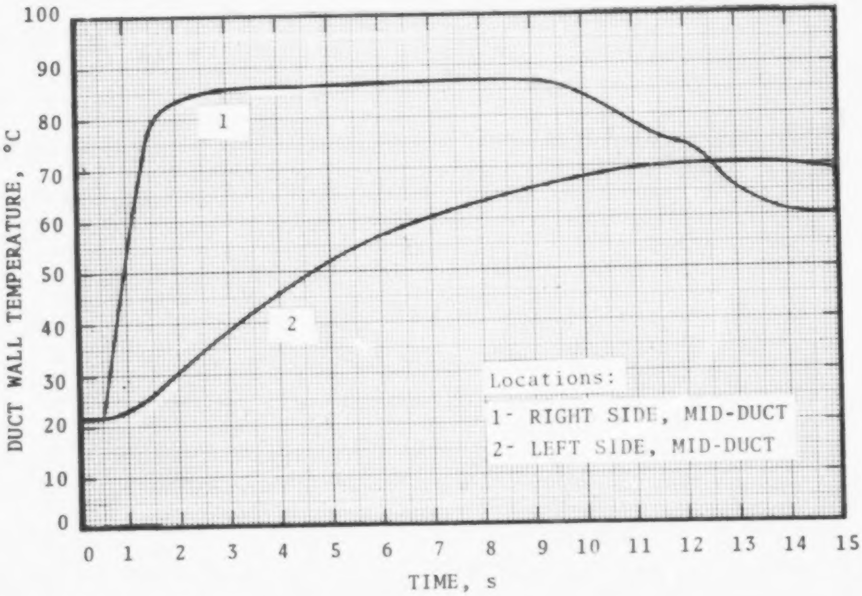


Figure 25. Test 4, scrubber duct wall temperature.

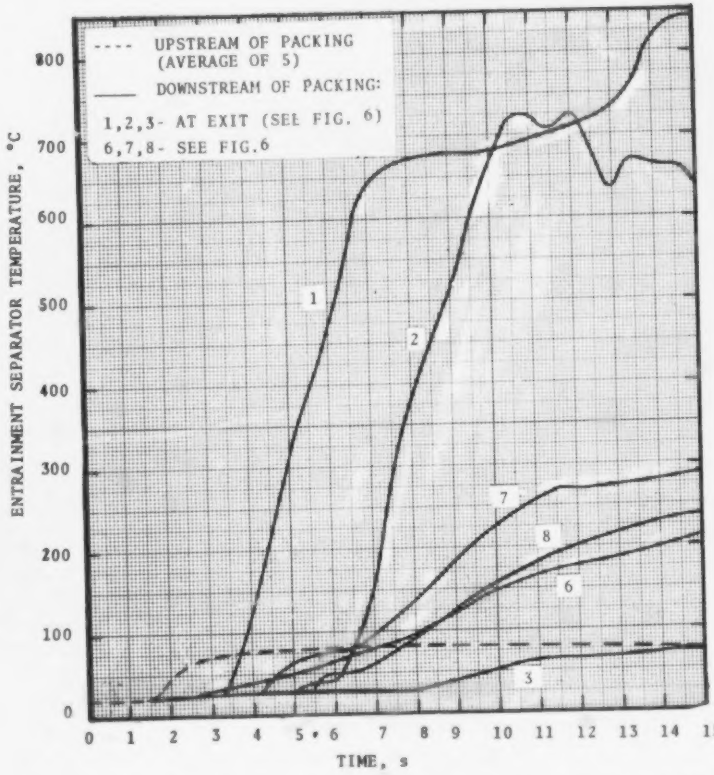


Figure 26. Test 4, gas temperature in entrainment separator from thermocouple arrays.

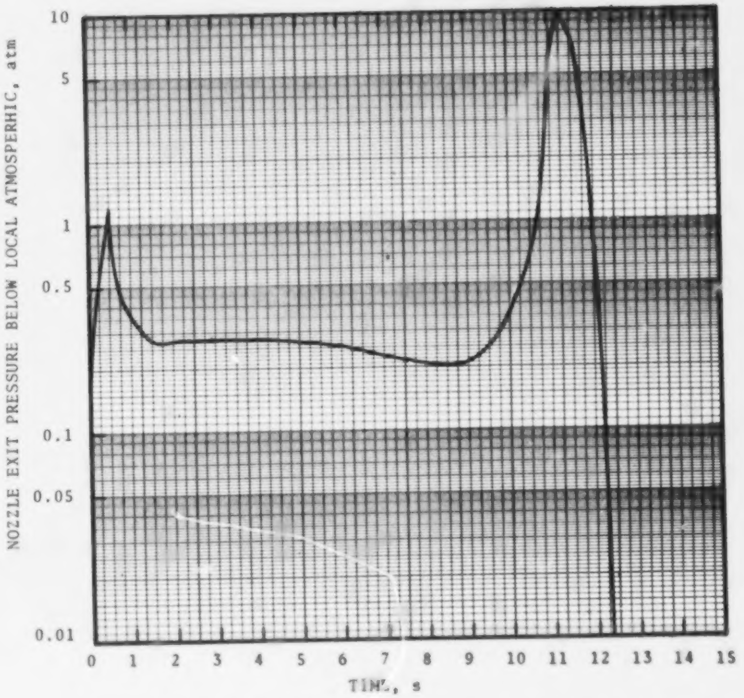


Figure 27. Test 4, pressure near rocket nozzle exit (diffuser inlet).

8), reached only 200-300°C. Contact with outside air seemed important to the temperature producing mechanism, which must surely be afterburning of hydrogen and carbon monoxide.

A new figure (27) is shown to illustrate the pressure felt at the inlet to the scrubber (or rocket nozzle exit). A differential transducer was used. Start-up and shut-down transients were quite apparent and could have an effect on thrust, depending on the area experiencing these pressures. Only one transducer was used in the test so that spatial variations in pressure were not measured. The data indicate positive pressure peaks at shut-down, which mean that short duration leakage was occurring. These leaks were seen in films of the tests but probably represented a very small amount.

Velocity Profile at End of Scrubber Duct -

The total pressure relative to atmospheric across the end of the scrubber duct is shown in Figure 28. The two center pressure taps were overpressurized to the extent that the manometer fluid was blown out. This indicated poor mixing in the duct which had not been experienced to such an extent in previous tests. A possible reason was that the rocket chamber pressure reached a higher level in this than in previous tests, causing a higher nozzle velocity.

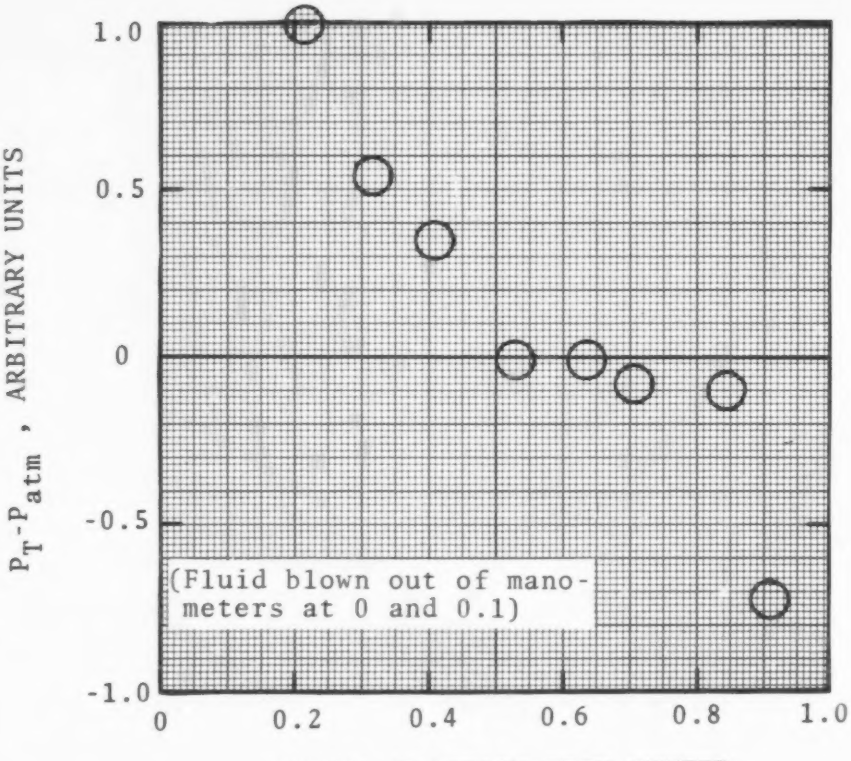


Figure 28. Test 4, velocity profile in scrubber.

CONCLUSIONS FROM AFRPL TEST PROGRAM

Much was learned about the basic design and practical aspects of the AFRPL gas-atomized scrubber. Most important, it worked and was not destroyed by the solid rocket exhaust. However, only tests of 10-second duration were made and there are serious doubts that the entrainment separator could withstand longer durations mainly because of afterburning effects. Also, the solid rocket motors tested had end burning propellant grains which produce more gradual thrust start and tail-off transients. Whether the scrubber could have withstood some of the rapid starting motors is questionable.

Scrubbing Efficiency

The aluminum oxide particles were collected with greater than 99% efficiency in the scrubber based on filter sampling and the gas exiting the scrubber had no discernible opacity. Since the gas sampling system was unsuccessful, the HCl removal efficiency can only be inferred from other observations. Chief among the other observations were the particulate collection experiments and visual opacity. These observations indicate that there was good contact between the rocket exhaust and the injected liquid which would also mean that good conditions for HCl absorption also existed.

Further reason to assume good HCl absorption was that the temperature and pressure measurements showed that mixing of the exhaust with the injected liquid was good. Theory of HCl absorption, which will be discussed later, indicates that the absorption will occur in a few meters provided the drops are thoroughly mixed with the gas.

Liquid Injection System

The angle-iron protected pipe injectors performed their function but could be improved. The first angle burned through during each test, which required that time be spent replacing it. Some of this maintenance time could be saved if a more heat resistant angle was used. Possibly a stainless steel angle, coated with an ablative or a ceramic, could be used.

The amount of liquid used (85-115 ℓ/s) was adequate, as theory predicted. However, not enough tests were conducted to determine the optimum rate. Also, the 3% by weight KOH solution seemed adequate, but may not be optimum. Because of the complexity that use of the KOH solution required it was questionable for an operational scrubber. As will be discussed later, the use of a basic solution is not essential for the mass transfer of the HCl into the scrubbing liquid. The neutralization could perhaps be more easily accomplished in the sump and the drying pond.

Diffuser

The "diffuser" served to direct the exhaust gases into the scrubber and to protect the front part of the scrubber from radiation heat damage. It suffered heat damage during each test. With the present design of the system this was unavoidable since the spray ring did not supply nearly enough water to keep the walls cool.

Entrainment Separator

The entrainment separator was very efficient, as evidenced by the low emission rate of aluminum oxide particulates. The particles were collected on drops in the scrubber with an efficiency greater than 99.9% so that the entrainment separator efficiency should be the same as the overall particulate efficiency based on the filter sampling. The start-up pressure transient was effectively relieved by the hinged hatches so that overpressurization was not experienced. Since the entrainment separator was so efficient it is suggested that the packing could be reduced in thickness somewhat. The reduction in packing thickness would partially alleviate the pressurization of the entrainment separator section.

Afterburning

A major finding of the solid rocket test program was the occurrance of afterburning. The high temperatures sensed by the exit thermocouples and the damage done to the sampling apparatus are clear evidence that the carbon monoxide and hydrogen exhaust gases were afterburning. This afterburning had some affect on the entrainment separator section. The packing and packing supports were slightly melted and charred. While the afterburning itself may not have been preventable its consequences could have been reduced by a different design. There was no basic design reason for the converging section after the packing. This convergent section was only there for the purpose of providing a smaller and more uniform section for sampling. It provided a region where air could collect, circulate and react with the combustible gases in close proximity to plastic and fiberglass surfaces. Had there been no convergent section any afterburning would have taken place at some distance above the structure, causing much less damage.

In order to minimize afterburning effects the gas direction leaving the entrainment separator should be vertical rather than horizontal. Also, the exiting gases should have as high a velocity as possible so that any afterburning will occur as far above the packing and structure as possible. Finally, the separator should be designed so that when the rocket is ignited all the air is forced out with the first blast of exhaust gas. There should not be any pockets of air left while the system is operating.

Sampling System

Sampling of the effluent gas was difficult because the afterburning melted the sampling lines and filters, and the velocity was not uniform. The array of filters for particulate sampling worked for the first test but holes were burned in the filters during the second test. Sampling with filters was abandoned after the second test. Gas sampling with evacuated bottles was unsuccessful because the sampling lines burned through. The afterburning, in effect, has made gas sampling practically impossible in the present type of system.

Sampling of the effluent liquid and sump could be done in a thorough fashion. A number of instruments could have been used to monitor the flow rate, turbidity, pH, and chloride ion concentration to provide a better indication of the scrubbing efficiency than was accomplished with the gas sampling system. Another possibility would be to collect all the effluent liquid, including the post-test rinse of the entrainment separator packing, in a tank for post-test analysis. For the 10-second tests an 800 liter (210 gallon) tank would be adequate.

Coupling Effects

The effect of the scrubber on the rocket test was not measured directly because thrust was not measured. One pressure transducer located beside the rocket nozzle exit did indicate ignition and burn-out transient peaks which could have affected thrust. The peaks were short duration so that their effect should be small. An array of transducers would be needed to determine the pressure distribution on the rocket nozzle in order to estimate thrust effects.

SECTION 5

AIR POLLUTION CONTROL EQUIPMENT ALTERNATIVES

INTRODUCTION

The purpose of this section is to review alternative air pollution control devices and present background information on equipment which has been used in similar applications. The most suitable approaches for the present application will then be presented.

SELECTION OF AIR POLLUTION CONTROL EQUIPMENT

Many types of equipment can be used for controlling emissions from stationary sources. These types include filters, electrical precipitators, cyclones, mechanical collectors, scrubbers, adsorbers, and combustors. In the case of the rocket exhaust the source is a supersonic stream of extremely hot gas. The pollutant of main concern is hydrogen chloride gas. Thus, the type of control equipment must be capable of collecting a very hot, very corrosive gas. Filters, electrical precipitators, cyclones, and mechanical collectors are primarily designed to collect particulate matter. Combustors are used mainly for oxidizing gaseous contaminants to non-toxic gases such as water and carbon dioxide. Scrubbers and adsorbers are the two types of equipment used most often for removing gas phase contaminants. Adsorbers retain contaminant gases on the surface of porous particles around which the carrier gas flows. Scrubbers introduce liquid into the collector to dissolve or react with the contaminant gas.

Adsorbers are not suited for the control of rocket exhaust for many reasons. Adsorption usually works best for adsorbates which are dilute, dry, and cool. In addition, particles of the adsorbent must be used to provide adequate surface area, creating the task of removing particulates which may be toxic. The only major industrial use of adsorption for removal of a gas similar to hydrogen chloride is the closed loop system for recycling hydrogen fluoride from aluminum smelting fumes (Cochran, 1974). The mechanism in this use is chemisorption on calcined alumina (Al_2O_3). Injection-type dry sorption using limestone to remove SO_2 from power plant boilers has been extensively tried, but found to be inefficient (Slack and Hollinden, 1975). Some adsorption of HCl will occur on the alumina particles generated by the rocket motor but this does not appear to accomplish more than a small fraction of the required transfer.

Liquid scrubbing processes are more attractive for removing rocket exhaust gases because water must be used to cool the gas and the mass transfer is good at the temperatures involved. Like the dry scrubbing process, if the scrubbing medium is sprayed into the gas stream, provision must be made to remove the added matter (drops).

Various types of liquid (wet) scrubbers are available for mass transfer. The types are plate, massive packing, fibrous packing, preformed spray, gas atomized spray, centrifugal, impingement and entrainment, moving bed, and combinations (Calvert et al., 1972).

A plate scrubber consists of a vertical tower with plates mounted transversely inside. Gas enters at the bottom of the tower and must pass through perforations, valves, slots, or other openings in each plate before exiting the top. Liquid is usually introduced at the top plate and flows successively across each plate as it moves downward to the liquid exit at the bottom.

Massive packing scrubbers consist of towers containing manufactured or natural elements. Liquid is usually introduced at the top and trickles down through the packing. The gas stream should not be too heavily loaded with particles or the packing will become clogged. Fibrous packing scrubbers are similar in principle to massive packing scrubbers except that fiber beds with very large void fractions are used.

A pre-formed spray scrubber collects particles or gases on liquid droplets and uses spray nozzles for liquid droplet atomization. The sprays are directed into a chamber suitably shaped to conduct the gas through the atomized liquid droplets. Centrifugal scrubbers with spray manifolds are a type of pre-formed spray scrubber that impart a spinning motion to the gas passing through them. This configuration reduces droplet carryover due to entrainment because the droplets are impacted upon the scrubber walls by centrifugal force.

Gas-atomized spray devices use a moving gas stream to atomize liquid into drops, and then accelerate the drops. High gas velocities (60-120 m/s) are used to promote particle collection and finely atomize the liquid which is introduced. Entrainment separators must usually be used.

Impingement and entrainment scrubbers are configured so that the entering gas must pass over a reservoir of liquid at a speed and direction which causes the gas to atomize and entrain the liquid. These devices usually have an entrainment separator built into the exit duct.

Moving bed scrubbers are like the packing scrubbers except the packing is usually spheres and these spheres move around during operation. Gas velocities are high to make the bed turbulent enough to keep the packing clean. Thus, this type is suitable for particulate as well as gas removal.

The efficiencies of the various scrubbers all depend on a number of factors and each can be designed to any desired efficiency. The primary factors affecting efficiency are liquid-gas contact surface area and contact time. Contact types of packing, plates, or spray atomizers. Contact time is regulated by packing height, number of plates, and spray chamber length.

EQUIPMENT FOR REMOVAL OF HCl and HF

Hydrogen fluoride is encountered more often than HCl as a serious industrial air pollutant in the stack gases from phosphate fertilizer plants, aluminum plants, and calcium phosphate furnaces. The high absorptivity of both HCl and HF in water has made scrubbing the most widely used removal means. Kohl and Riesenfeld (1960) review several scrubbers used for HCl tail gas removal. Most use a packed tower with water as the absorbent. Scrubbers for HF removal have been reviewed by Magill et al. (1956), Kohl and Riesenfeld (1960), and Teller (1967). They describe a number of spray, packed tower, and venturi scrubbers that have been used. Magill also describes HF removal by passage through beds of lump limestone to produce calcium fluoride in fine particulat form.

In the recent literature Kempner et al. (1970) tested several packed, plate, and spray tower hydrogen chloride scrubbers. Tomany (1969) describes a moving bed scrubber used on an aluminum processing plant. Rust et al. (1973) also describe a number of scrubbers for use on aluminum smelters.

In recent years hydrogen fluoride has been recovered during aluminum smelting by chemisorption on calcined aluminas (Cook et al., 1971). Since solid propellant rockets produce alumina (Al_2O_3) this may be a possible removal mechanism for both HF and HCl. The problems with this process for rocket exhaust scrubbing are that the reaction occurs at low temperatures and aluminum fluoride dust is produced (Cochran, 1974). Although at present the technology is not directly applicable to the rocket exhaust, further study and development of the process could make it attractive.

SCRUBBERS USED ON HIGH ENERGY EXHAUSTS

Aside from rockets the major producer of high temperature, high speed exhaust gas is the jet engine. While the jet engine does not produce much toxic gas the scrubbing of its particulate emissions involves similar means. In the following a number of scrubbing facilities will be described which are applications similar to the solid rocket exhaust. While a number of such scrubbers are known to have existed, only those for which a reasonable amount of information was obtained will be discussed.

Naval Air Rework Facility
Jacksonville, Florida

This facility operates a jet engine test cell that has a pollution abatement system for particulate removal. The control system consists of a quencher and a cross flow packed scrubber designed by Teller Environmental Systems, Inc. The entrainment separation was accomplished by an additional section of dry packing. The system is sized so that the superficial velocity is in the range of 2.5 - 5 m/s. According to tests performed in a similar model system, considerable particulate removal occurs in the quencher section as the gas is cooled. The conditions and efficiencies for two jet engines at military power were as follows (Kemen, 1976):

J52 Engine

Thrust	37,000 N (8,300 lbf)
Volumetric Flow Rate	154 m^3/s at 15°C
Exhaust Temperature	~800°C
Heat Release	38 MJ/s

J79 Engine

Thrust	49,000 N (11,000 lbf)
Volumetric Flow Rate	135 m^3/s at 15°C
Exhaust Temperature	~800°C
Heat Release	47 MJ/s

Particle Scrubbing Efficiency

Engine	J52	J79
Quench, Q_L/Q_G, ℓ/m^3 at 15°C	0.29	0.33
Gas Velocity in Scrubber, m/s	3.6 to 4.1	
Particle Loading, mg/m^3 at 15°C	23	55
Efficiency, %	74	81

Particle size data were not available.

Arnold Engineering Development Center
Arnold Air Force Station, Tennessee

The AEDC is a complex of wind tunnels, propulsion test cells, aerospace chambers, and hyperballistic ranges. Their Engine Test Facility has a number of test cells for testing rockets at simulated altitudes and Mach numbers. The high altitude (low pressure) is accomplished primarily by steam ejector-diffusers during prefire and by the rocket exhaust gas ejector action during the firing. High velocities are obtained through a combination of ejector-diffusers, air supply compressors, and exhaust compressors. Two of the larger test cells (J-4 and J-5) use spray chambers to cool and dehumidify the exhaust gases. In cooling the exhaust gases these cells also effectively scrub particulates and soluble gases. Performance of these test cells as scrubbers has not been reported, however.

The test cells at AEDC are not designed for low altitude (sea level pressure) testing. Low altitude testing requires that the cells be maintained at local atmospheric pressure. This could be accomplished by opening up the cells. However, the increased gas density at the higher pressure would put too high a load on the exhaust system. Either the compressors would overload or the ducting system would be overpressurized. The problem would be particularly severe at rocket ignition when the large mass of air resident in the system has to be moved at a very high rate as the rocket plume enters the exhaust system.

Toxic Attitude Propulsion Research Facility
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

The TAPR facility is designed to allow safe ground-testing of toxic propellants in simulated high altitude environments. Steam ejector-diffusers are used to pump the system to the desired pressure. Spray chambers to cool the rocket exhaust are also incorporated in the facility design. The facility is described in *Aviation Week* (1967).

As with the AEDC test cells, the spray chamber acts as a scrubber for particulates and soluble gases. It was estimated to be 95% efficient on soluble effluents but some unpublished data showed that it may be less efficient. A thorough study of its scrubbing efficiency has not been published.

The facility, like those at AEDC, is not designed for low altitude (high pressure) testing. The problems that would be encountered during atmospheric pressure testing have been briefly described previously.

Jet Propulsion Laboratory - Edwards Test Station
Edwards Air Force Base, California

JPL-ETS operates a rocket engine toxic exhaust scrubber facility described by Frank C. Brown (1969). The scrubber was designed to operate on a 1,000-second duration, 9,000 N (2,000 lbf) thrust liquid rocket. The oxidizer and fuel were OF_2 and B_2H_6, and the reaction products were HF, BOF, and H_2O.

The scrubber uses a two-step alkaline water solution starting at the exit of a diffuser which ducts the rocket exhaust gases from the rocket nozzle to the spray scrubber. Sodium hydroxide is used in the first step during rocket operation, and calcium hydroxide is used in the second step either during or after rocket operation. During the second step the sodium hydroxide is reconstituted and fluorinated and boronated calcium compounds are precipitated out and later removed physically.

The gas-liquid contact occurs in a 0.91 m diameter by 9.1 m long horizontal, co-current spray duct which exhausts downward through an elbow into the sump. The gas must then turn upward to flow through a vertical packed tower. The tower has a wet stage for more scrubbing and a dry stage for entrainment separation. The liquid flow rate in the spray chamber is 151 ℓ/s and in the tower it is 63 ℓ/s. An axial fan is used at the tower exit to maintain a negative system pressure.

The system is designed to reduce the concentration of fluorine or boron in the effluent to 3 ppm or less. Considering that almost all the combustion products need to be removed this represents a very high efficiency. However, such a high efficiency is probably not unrealistic since the flow rate of scrubbing liquid was about 90 times the mass flow rate of the rocket propellant. This compares to the 10-15 factor used for the design of the AFRPL pilot scrubber.

Other Facilities

A few other rocket exhaust scrubbing facilities have been briefly described in the Phase I report (Calvert and Stalberg, 1975). They represent efforts by several contractors to reduce the emission of primarily hydrogen fluoride gas or beryllium oxide particles. Most designs use the nozzle spray or gas-atomized spray design quencher/scrubber followed by an entrainment separator. As usual, reports on the efficiency of these scrubbers have not been published.

POTENTIALLY SUITABLE SCRUBBERS

Because of the requirement for gas absorption a wet scrubber is the type of equipment that should be used. No other type of device has been used so extensively and successfully for gas removal. Also, scrubbers that are highly efficient for gas absorption are usually highly efficient for particle collection. All the types of scrubbers can be designed to meet the required efficiency. Thus, selection of one particular type will depend primarily on economic factors. Most designs for rocket exhausts, or similar processes, have been a spray chamber followed by a packing for extra scrubbing and entrainment separation (mist elimination). This spray scrubber design is probably the least expensive approach since all the designs will require a quencher and the quencher can be an integral part of the spray scrubber. The economic selection of the scrubber will be detailed in the next section.

SECTION 6
DETAILED DESIGN

DEFINITION OF THE SCRUBBING PROCESS

The scrubbing process required for the solid rocket exhaust is primarily high efficiency gas absorption. Particle collection will also be accomplished at an efficiency which depends on the type of scrubber chosen. While the particulate pollutant emissions in question were not considered a problem of concern in the desert air basin portion of San Bernadino County, there might be a significant restriction in the case of other pollutants and/or other jurisdictions. Therefore, attention is given to both gas absorption and particle collection in this section.

The problems associated with the very high energy, high volume flow rate, and short duration of the rocket exhaust distinguish this absorber from those found throughout the process industry. Conventional configurations can be utilized but the peculiarities of "rocket scrubbing" lead one to consider the possibilities for unconventional approaches.

Simplified Process Flow Sheet

The general nature of the control process for the rocket exhaust is shown in Figure 29. The four main components shown are:

1. Quencher
   Here the rocket exhaust is cooled and slowed by massive amounts of injected water. The gas leaving the quencher is saturated with water vapor and the velocity is low enough to be more amenable to particle and gas scrubbing. Some pollutant collection will take place in the quencher.
2. Scrubber
   In this section the gaseous pollutants are absorbed and

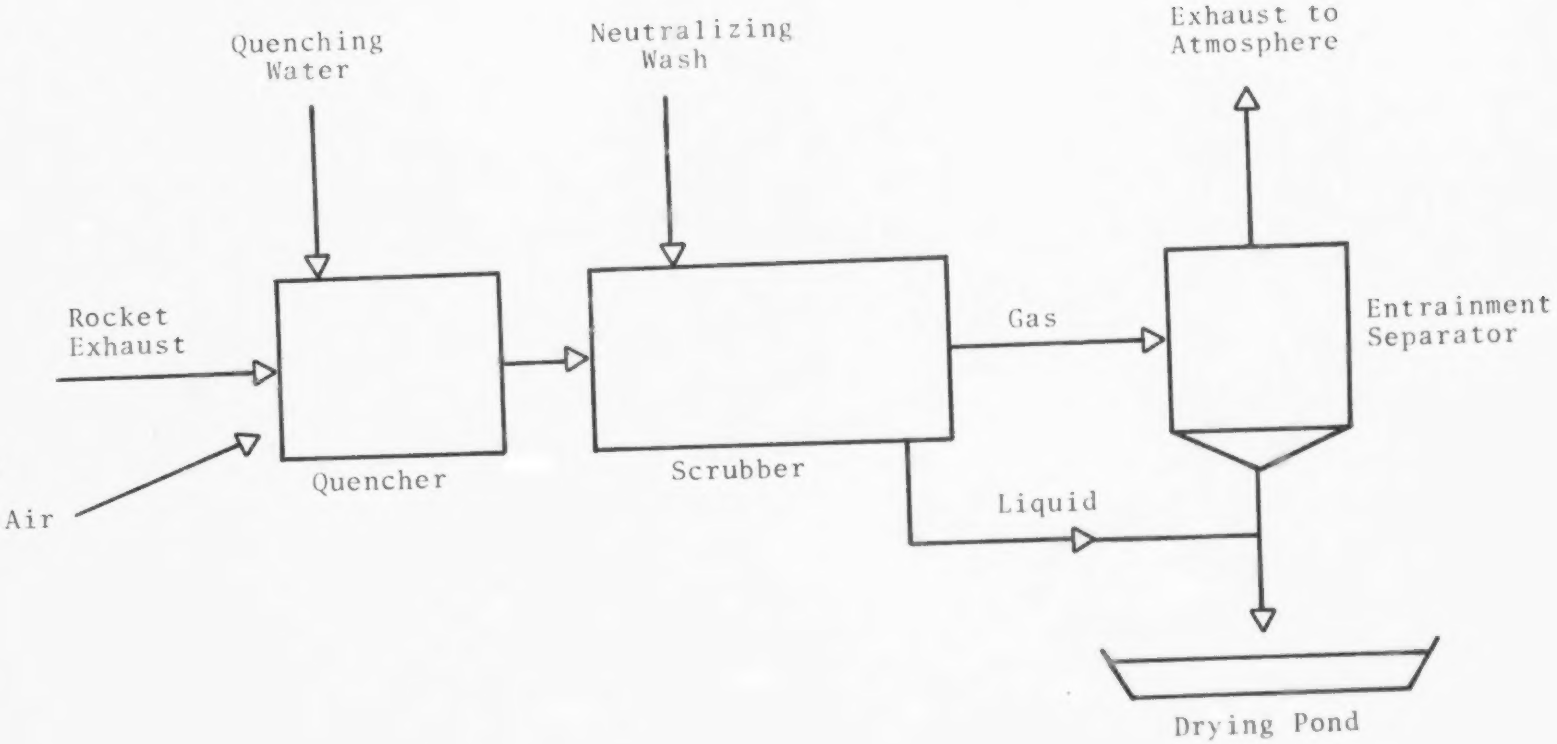

Quenching Water
Neutralizing Wash
Exhaust to Atmosphere
Rocket Exhaust
Air
Quencher
Scrubber
Gas
Liquid
Entrainment Separator
Drying Pond

Figure 29. Schematic of rocket exhaust gas scrubbing process.

particulate pollutants are collected. In some scrubbers, such as the gas-atomized design, this section could be integral with the quencher.

3. Entrainment Separator
   Liquid drop carry-over from the scrubber is collected here. If a neutralizing agent is used in the scrubber this section is not absolutely necessary under the local APCD rules (see Section 3), but several other factors could justify its use.
4. Drying Pond
   The scrubber and entrainment separator liquid effluent should generally be collected in a drying pond rather than be allowed to pollute the ground water.

Quenching Equilibrium

Basic to the design of a scrubber for solid rocket exhausts is the calculation of flow conditions at the inlet to the scrubber. The first and simplest calculations are the equilbrium balances of mass, momentum, and energy in the quencher. The required liquid injection system and mixing length in order to achieve these equilibria will be discussed later.

As will also be discussed later, two scrubber designs, which have different types of quenchers, will be proposed. The equilibrium conditions presented here will be appropriate for each of the types of quenchers.

Ideal Gas Law -

The ideal gas law is adequate to define P.V.T. relationships for the gases of the rocket exhaust, air, and water vapor at near atmospheric pressure. With the subscripts "v" and "g" representing water vapor and non-condensing gases, respectively:

$$P_v = \frac{n_v R_u T}{Q} \qquad (11)$$

$$P_g = \frac{n_g R_u T}{Q} \qquad (12)$$

$$P = P_v + P_g \qquad (13)$$

where P = pressure, N/m^2 (Pa)
n = mole flow rate, kgmol/s
R_u = universal gas constant, 8,314 J/kgmol-°K
T = temperature, °K
Q = volume flow rate, m^3/s

Since "P" is known or can be easily approximated and "n_g" is known from the composition of the rocket exhaust and the amount of entrained air these equations are rearranged to give:

$$Q = \frac{n_g \; R_u \; T}{P - P_v} \qquad (14)$$

$$n_v = \frac{P_v \; n_g}{P - P_v} \qquad (15)$$

"P_v" can be found from the vapor pressure relationship for water.

Vapor Pressure of Water Solutions -

To assure quenching, enough water is assumed to be used to saturate the gas at the equilibrium pressure and temperature. The following equations are based on the assumption that some liquid water is present.

The vapor pressure of pure water is related to temperature in accordance with the following equation:

$$\log_{10}(P_{v,pure}) = a - \frac{b}{T + c} \qquad (16)$$

where $a = 5.84191$
$b = 1668.21$
$c = -45.$
for $333° \leq T \leq 433°K$

$$T = \frac{b}{a - \log_{10}(P_{v,\text{pure}})} - c \qquad (17)$$

Dissolved species cause a depression of the vapor pressure. At a given temperature the depression may be represented as:

$$\frac{P_{v,\text{pure}}}{P_v} = 1 + c_1 \chi^{c_2} = d' \qquad (18)$$

where c_1 and c_2 = constants
χ = concentration of the salt solution

Thus:

$$T = \frac{b}{a - \log_{10}(P_v\ d')} - c \qquad (19)$$

Mass Equilibrium -

The total mass flow rate (m) must equal the mass flow rates of the rocket exhaust, m_r. the entrained air, m_a, and the injected liquid, m_w.

$$m = m_r\ (1 + R_a + R_w) \qquad (20)$$

where m = mass flow rate, kg/s
R = mass ratio, kg/kg

The volume flow rate of gases is:

$$Q = u\ A \qquad (21)$$

where u = velocity, m/s
A = cross sectional area of mixing section, m^2

The volume of liquid and solid particles is neglected. The velocity is then:

$$u = \frac{Q}{A} \tag{22}$$

Momentum Equilibrium -

The momentum balance requires that the vector sum of the forces acting on a control surface equals the vector change in momentum within the volume enclosed by the control surface. For the case of an open quencher, with all pressures being equal, the only external force is the resistance force due to obstacles and wall friction. Thus:

$$F = F_D + m\ u \qquad \text{(open)} \tag{23}$$

where F_D = drag (resistance) force, N
F = rocket thrust, N

The flow was assumed to be one dimensional and the injected liquid was assumed to contribute no momentum in the flow direction. The velocity of the air was also assumed to be negligible. For the closed, ducted quencher pressure forces are present. In this case the resistance forces are usually small in comparison with the other forces and can be neglected. So:

$$F + P_{in}\ (A - A_e) = m\ u + P\ A \qquad \text{(closed)} \tag{24}$$

where P_{in} = pressure at quencher inlet, N/m^2
A_e = rocket nozzle exit area, m^2

Solving for "P_{in}":

$$P_{in} = \frac{m\ u + P\ A - F}{A - A_e} \tag{25}$$

"P_{in}" is the pressure at the quencher inlet due to the ejector action of the rocket. It is not as well defined as "P". The equilibrium pressure, P, is the pressure above atmospheric by the amount equal to the scrubber/entrainment separater pressure drop.

Composition and Chemical Reaction Balances -

The gas composition may change in the quencher because of reactions of hydrogen and carbon monoxide with oxygen in the entrained air and reactions of the hydrogen chloride or hydrogen fluoride with bases in the injected liquid (if any).

CO and H_2 react with the oxygen in the entrained air:

$$CO + H_2 + O_2 \rightarrow CO_2 + H_2O$$

Because of the assumed absence of catalysts for the reverse reactions (e.g., the "water-gas" reaction), the amount of CO and H_2 can only reduce.

The oxygen is assumed to react completely. Thus:

$$n(O_2) = n(O_2)_a - \tfrac{1}{2}\left[n(CO)_r + n(H_2)_r\right] \qquad (26)$$

$$n(CO) = n(CO)_r - n(O_2) \qquad (27)$$

$$n(H_2) = n(CO)_r + n(H_2)_r + 2\left[n(O_2) - n(O_2)_a\right] - n(CO) \qquad (28)$$

The notation "n(species) is the molal flow rate of the species in parentheses.

Energy Balance -

The static enthalpy of the rocket exhaust products is:

$$n_r\, h_r(@T_r) = \sum_i n_i \left[h_i\,(@T_r) - h_i(@298°K) + \Delta h_{fi}(@298°K)\right] \qquad (29)$$

where "i" refers to the various components of the rocket exhaust, and:

h = enthalpy per mole, J/kgmol

Δh_f = enthalpy of formation per mole, J/kgmol

The enthalpy of the air is assumed to be zero since the temperature is close to 298°K. The enthalpy of the injected liquid is assumed to be the enthalpy of liquid water at 298°K.

The final equilibrium enthalpy is just:

$$\sum_j n_j \; h_j(@T)$$

where "j" represents all species present at equilibrium.

The energy balance must account for the change in kinetic energy as well as the change in enthalpy, so:

$$n_r \; h_r(@T_r) + n_\ell \; h_\ell \; (@298°K) + \tfrac{1}{2} m_r \; u_r^{\,2} = \sum_j n_j \; h_j(@T) + \tfrac{1}{2} m \; u^2 \qquad (30)$$

Solution of Equilibrium Equations -

A Fortran computer program has been written to provide a solution to the equilibrium equations and is presented in the appendix "A".

Comparison with Garrett

As a check on the equilibrium predictions made by the computer program described above, a comparison was made with a previous prediction by Garrett et al. (1972). The prediction is for a 22 kN (5,000 lbf) solid rocket exhausting into a scrubber duct that is 0.914 m (3 ft) in diameter, similar to the AFRPL pilot scrubber. The parameters used in the prediction are presented in Table 9. The velocity and temperature predictions are shown in Figures 30 and 31. The two velocity predictions are very close and the temperature predictions are different by only 2 to 5 degrees Celsius. The slight temperature difference may be due to different methods of calculating the equilibrium energy balance.

The present prediction program has several features that are not present in Garrett's program. Among these are a more precise method of calculating the equilibrium energy balance, provision for heat release to form the salt, and provision for vapor pressure depression due to dissolved salts.

TABLE 9. PARAMETERS FOR COMPARISON WITH GARRETT (1972)

ROCKET EXHAUST COMPOSITION AND STATIC ENTHALPY			
Component	Mole Fraction	Enthalpy Relative to 298°K kJ/gmol	 kcal/gmol
CO	0.2047	73.22	17.50
CO_2	0.0212	118.25	28.26
H_2O	0.1652	94.39	22.56
HCl	0.1688	70.53	16.86
Al_2O_3(S)	0.0756	230.90	55.18
N_2	0.0841	72.46	17.32
H_2	0.2531	68.38	16.34

Total Enthalpy = 182 kJ/gmol (43.42 kcal/gmol)
Total Molecular Weight = 29.0
Specific Impulse = 2,571 m/s (262.2 s)
Mass Flow Rate = 8.655 kg/s (19.08 lbm/s)
Thrust = 22.241 kN (5,000 lbf)
Diffuser Exit Area = 0.0323 m^2 (50 in^2)
Scrubber Area = 0.6567 m^2 (7.07 ft^2)
Scrubber Pressure = 0.94 atm (13.8 lbf/in^2)
Air Inbleed = 0.1 kg air/kg propellant
No heat of reaction to form KCl
No depression of water vapor pressure due to dissolved salts.

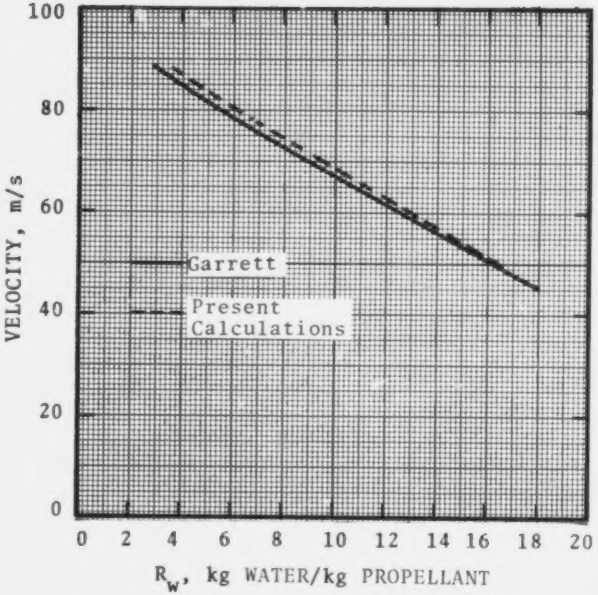


Figure 30. Comparison of velocity prediction with Garrett, et al. (1972).

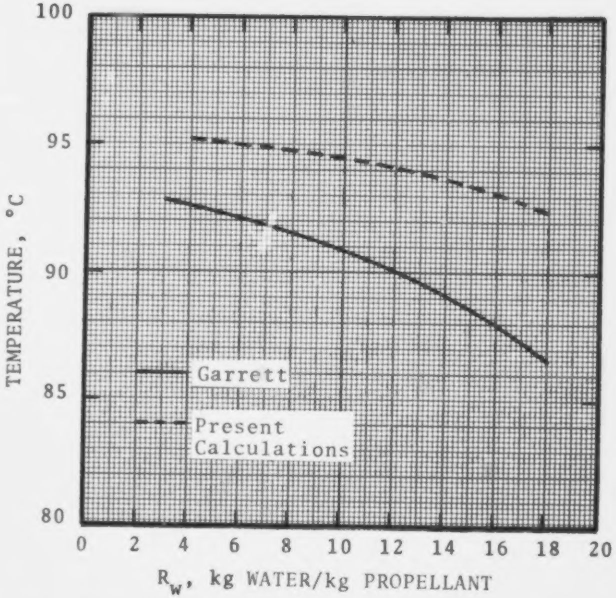


Figure 31. Comparison of temperature prediction with Garrett, et al. (1972).

Quenching Equilibrium Predictions

Closed Duct -

The computer program described in Appendix "A" was run to predict the quenching equilibrium conditions for a closed, ducted quencher. The equilibrium (exit) pressure was assumed to be 0.90 atm (13.2 lbf/in^2) and the rocket composition and conditions were those of the composite propellant rocket described in Section 2. Air was assumed to be entrained by the ejector action of the rocket exhaust in the amount of ten percent of the rocket mass flow rate. This air inbleed amount is somewhat arbitrary and will be discussed later. The hydrogen chloride gas in the rocket exhaust was assumed to dissolve in the liquid water, with consequent heat release and depression of the water vapor partial pressure.

The 2 meganewton (450,000 lbf) rocket was used in the computation. However, all the predictions, which will be shown, except the volume flow rate hold for any size rocket provided that the propellant composition and other parameters not related to size are the same, and the following ratio is used:

$$\frac{\text{Thrust}}{\text{Duct Cross Section}} = 40{,}000\ \text{N/m}^2\ (16{,}500\ \text{lbf/ft}^2)$$

This ratio was selected to provide a water vapor saturated condition and a velocity of about 100 m/s trading off liquid usage and duct diameter. It also provides a near maximum pressure rise (or suction) in the scrubber (Figure 25). A summary of the imput parameters for the predictions is given in Table 10.

The ratio of quenching water mass flow rate to rocket propellant mass flow rate was varied from about 3.5 (the minimum)to 20. The predictions are shown in Figures 32 to 37. The temperature in Figure 32 rises above the normal saturation temperature (97°C at 0.9 atm) because of vapor pressure depression caused by dissolved HCl. The pressure rise shown in Figure 34 illustrates the strong ejector action of the rocket exhausting

TABLE 10. PARAMETERS FOR 2 MEGANEWTON ROCKET QUENCHING PREDICTION

Rocket Exhaust Composition and Static Enthalpy
- As given in Tables 1, 2, and 4

Total Enthalpy = 194 kJ/gmol (46.4 kcal/gmol)

Specific Impulse = 2,590 m/s (264 s)

Mass Flow Rate = 772.2 kg/s (1,702 lbm/s)

Thrust = 2 MN (450,000 lbf)

Exit Area* = 1.53 m^2 (16.5 ft^2)

Duct Cross Section = 50 m^2 (538 ft^2)

Equilibrium (Exit) Pressure = 0.9 atm (13.2 lbf/in^2)

Air Bleed Fraction = 0.10 kg air/kg rocket exhaust

HCl Heat of Solution = 74,800 kJ/kgmol (48,900 kcal/kgmol)

*Based on a thrust coefficient of 1.68 which is appropriate for a chamber pressure of 10,300 kPa (1,500 lbf/in^2) and a ratio of specific heats of 1.15.

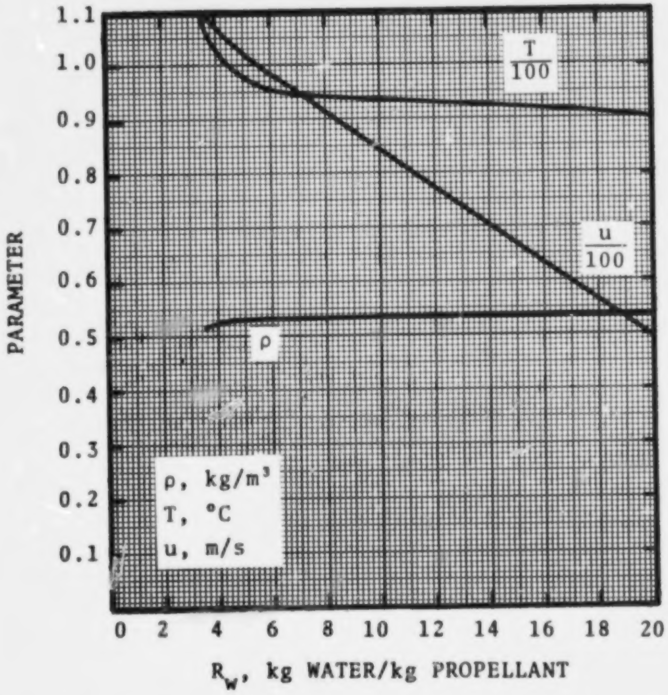


Figure 32. Flow conditions in a closed quencher.

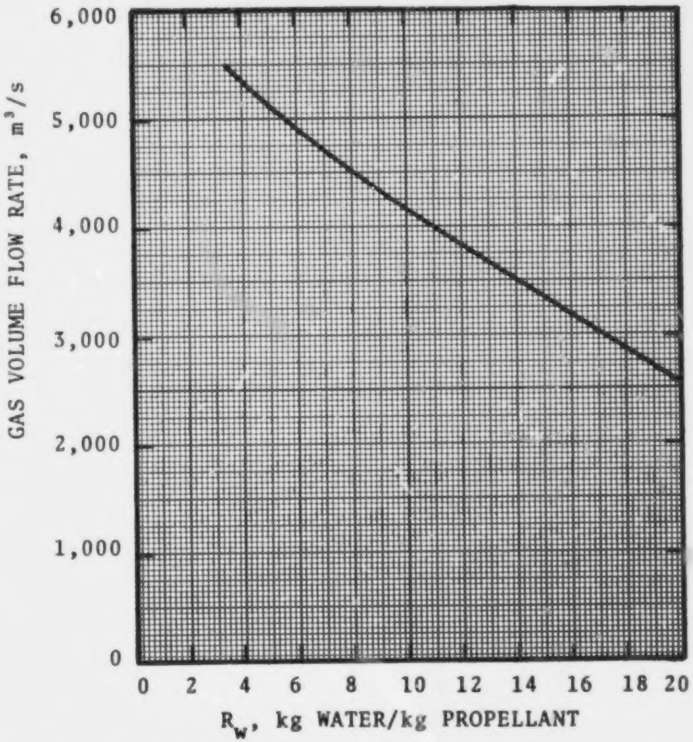


Figure 33. Gas volume flow rate of 2 MN rocket closed quencher.

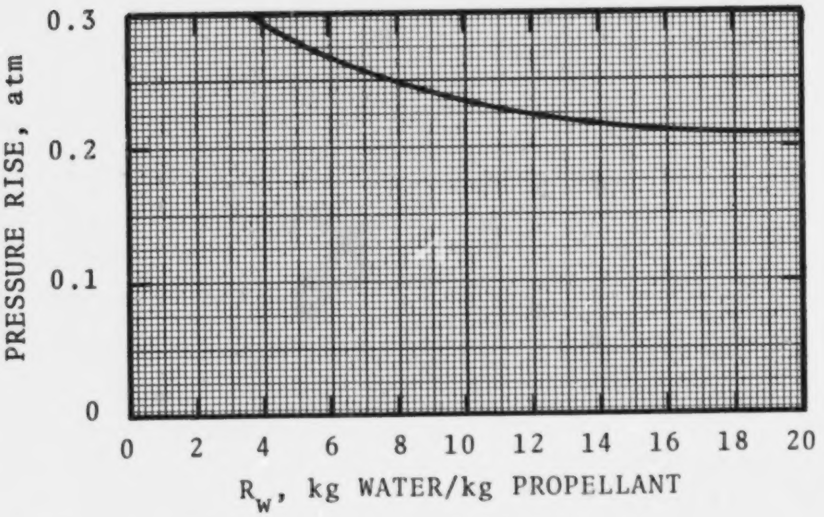


Figure 34. Pressure rise in quencher.

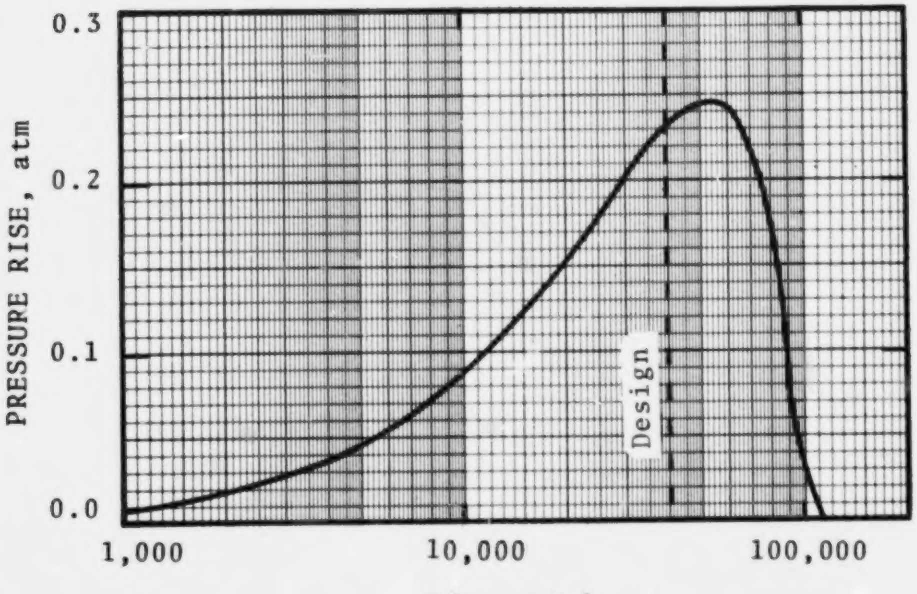


Figure 35. Pressure rise versus thrust to duct area ratio.

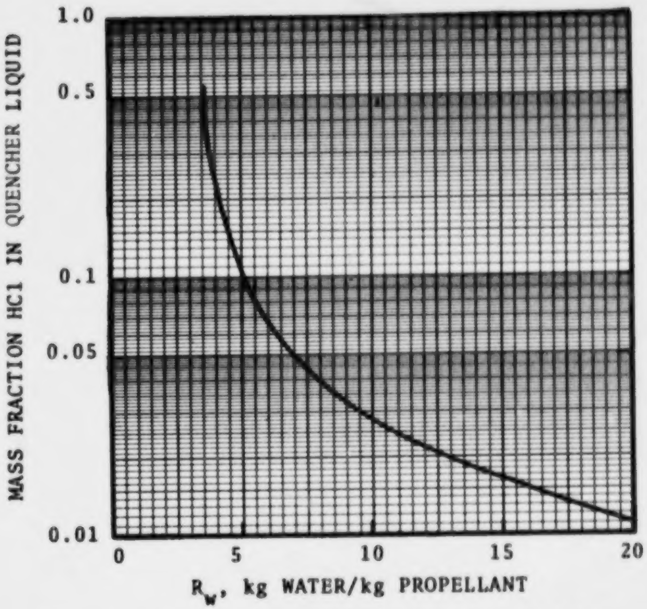


Figure 36. Concentration of HCl absorbed in quencher liquid.

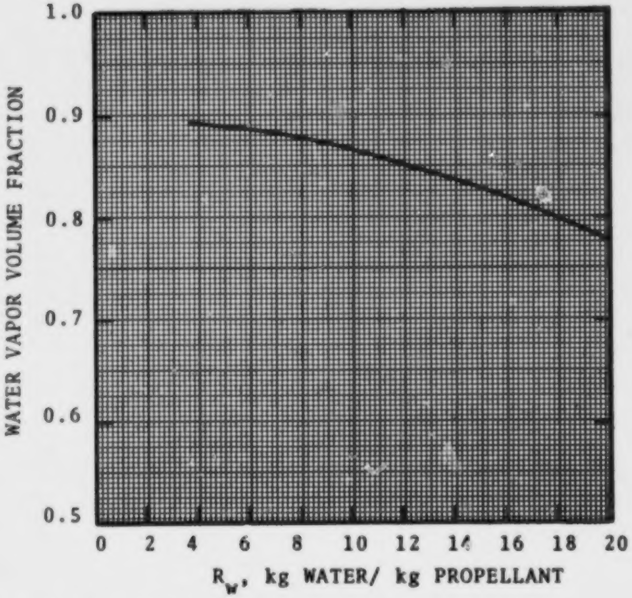


Figure 37. Water vapor volume fraction.

into the duct. It shows that a higher back pressure than 0.9 atm (absolute) is allowable before the rocket exhaust would spill around the duct. Figure 35 is a plot of the pressure rise for other than design thrusts based on R_w=10 and R_a=0.1 to determine the range of thrusts allowed for a certain design duct size. When the pressure rise is too low the rocket will begin to be a poor ejector and spillage will occur. Figure 35 is shown for a water ratio of 10 but will be similar for other ratios between 5 and 15. The HCl concentration abosrbed in the scrubber liquid (neglecting solids) is shown in Figure 36. It is important to note that for water/propellant mass ratios below 5 the liquid is very concentrated with HCl. The high concentration would tend to negate the assumption that no gaseous HCl exists in the quencher outlet because of the higher vapor pressure. However, the fraction of HCl gas would be very small since so much water vapor is present. The water vapor fraction is shown in Figure 37 and the gas composition is shown in Table 11.

TABLE 11. EQUILIBRIUM QUENCH COMPOSITION

Gas	Dry Basis Mole Fraction	Total Gas Mole Fraction @ R_W = 10
CO	0.267	0.036
CO_2	0.054	0.007
HCl	0 *	0 *
H_2	0.421	0.058
H_2O	0	0.864
N_2	0.258	0.035
O_2	0	0
Molecular Wt.	17.9	18.0

*The mole fraction of HCl would not actually be zero at low values of R_W ($R_W \leq 8$).

Open Channel -

A slightly modified computer program was used to compute quenching equilibrium conditions in an open quencher. Constant pressure throughout the system was assumed so that the flow area became a predicted variable. The parameters were the same as used for the ducted quencher (Table 10). The prediction of flow area, velocity, temperature and density are shown in Figure 38. The water vapor fraction and HCl concentration are very similar to those for the ducted quencher. The volumetric flow rate can be obtained from the area and velocity curves.

This prediction is based on several rough assumptions. Air is assumed to mix completely with the rocket flow and only in the amount equal to 10% of the rocket mass flow. Estimation of the amount of entrained air and the rate of mixing is very tedious except for completely open systems. Models for plume mixing with air only are given in CPIA Publication 263 (1975) but these are not applicable here because of the water addition, and because walls and other boundaries may be present.

Afterburning Considerations

Solid rockets produce and emit considerable amounts of hydrogen and carbon monoxide. These gases will react with oxygen in the air to produce water and carbon dioxide under the proper conditions of concentration, mixing, velocity, and temperature. Table 12 presents the accepted flammability limits and spontaneous ignition temperatures. If the combustion occurs in an enclosed structure the violence of the reactions may cause explosions. Normal, open-air, rocket firings are accompanied by almost complete afterburning of hydrogen and carbon monoxide since very little CO or H_2 is detectable in the vicinity of the rocket.

The use of an enclosed design for an exhaust gas scrubber required consideration of the possibility of combustion. Methods for controling the potential combustion are:

TABLE 12. COMBUSTION PROPERTIES OF H_2 and CO IN AIR AT STANDARD CONDITIONS

Gas	Stoichiometric Mixture % by Volume	Flammability Limit, % by Vol. Lower	Upper	Spontaneous Ignition Temp. °C
H_2	29.50	4.0	74.2	571
CO	29.50	12.5	74.2	609

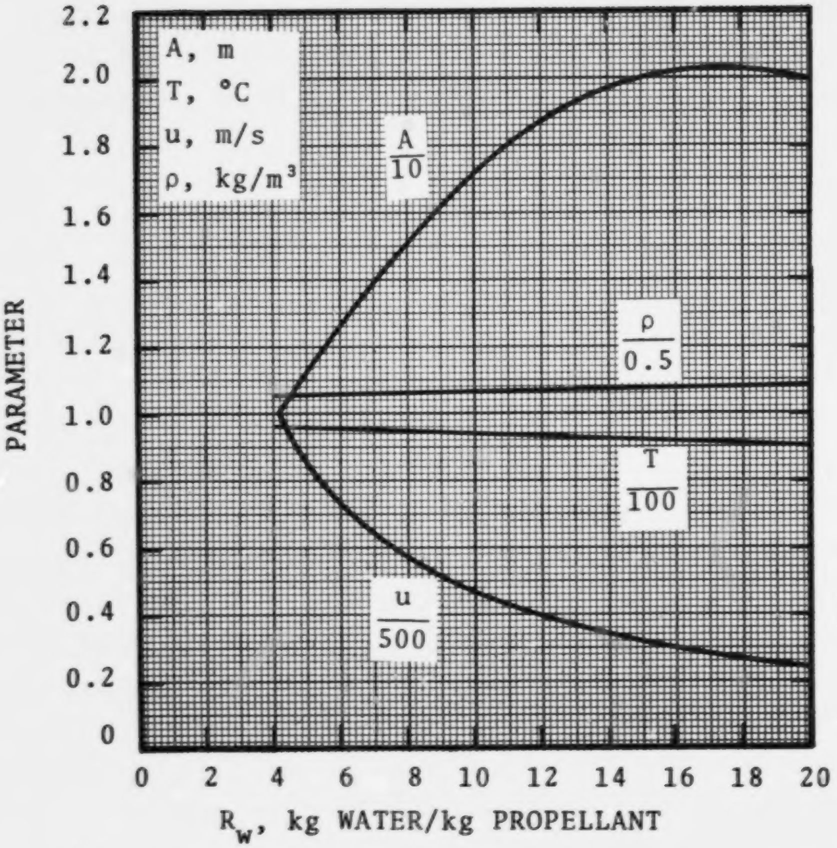


Figure 38. Flow conditions in an open quencher.

1. Limiting the amount of air entrained into the system so that combusion, if any, is slight.
2. Keeping the gas mixtures too cool to spontaneously ignite.
3. Removing all spark or charge producing mechanisms which would ignite the gases by grounding, etc.
4. Purposely burning the hydrogen and carbon monoxide with afterburners under controlled conditions.

The following discussion explains these four considerations.

Entrained Air -

The rocket itself acts as an ejector, which is a type of pump. The gas (air) that surrounds the nozzle exit is entrained by the nozzle exhaust and pumped into the scrubber. Charts for the amount of pumping by single-stage ejectors, such as are given in section 5 of Perry & Chilton (1973), may be used to estimate the amount of entrained air. The ejector charts overestimate the entrainment because complete mixing of the entrained and pumping gases is assumed. In most scrubbers the ratio of the diffuser duct area to the rocket nozzle throat area would be between 15 and 20. For this range of area ratios the amount of entrained air is between 10 and 20 percent of the rocket exhaust. Since these percentages represent an overestimate, the 10 percent value is the more correct figure. This 10 percent value was used by Garrett (1972) and for the baseline case presented in this report.

Limitation of this small amount of entrained air by closing the gap between the rocket nozzle exit and the diffuser of the scrubber is not a good idea. For very small gaps the pressure in the gap would be much lower than atmospheric because the air would have a high velocity due to the flow constriction. The pressure distribution on the outside of the rocket nozzle would then be other than uniformly atmospheric and cause incorrect thrust measurements. The possibility of direct attachment of the rocket nozzle to the scrubber diffuser also exists. The seal for such an attachment would have to be unable to transmit axial loads to the rocket nozzle but be able to withstand the high temperature environment. Also, the seal would be subject to the wall friction forces from the rocket gases. Such a seal may be possible but the design is not obvious.

Cooling -

The second means of reducing the possibility of combustion is to keep the gases below the temperature of spontaneous ignition. In a wet quencher the injected water enters directly into the supersonic exhaust stream so that cooling is initiated while the flow is too fast for combustion. By the time the flow has slowed to subsonic velocities the evaporating water has cooled the flow to below the boiling point of water. The boiling point of water is considerably below the spontaneous ignition temperature of the gases.

Static Electricity -

The third means of reducing the possibility of igniting the exhaust gases is to remove spark or charge producing mechanisms from the scrubber. The solid aluminum oxide particles acquire charges because of the extreme temperatures in the rocket chamber where they were formed, and by friction with the surrounding gas ions and particles. Water droplets acquire charges because of their contact and friction with the high speed, hot rocket exhaust. The charging of the particles due to high temperatures and friction is unavoidable. These particles flowing in the scrubber may induce electrostatic fields in the scrubber walls and be attracted to the walls.

Under severe charge concentration conditions the particles could discharge at the walls with an accompanying arc or spark. These severe conditions were not thought likely to occur because the size of particles required to hold large enough charges to discharge with an arc is much larger than is expected from the rocket exhaust. Additionally, both the particles and the scrubber walls would have to have high resistivities so that the charges would not be easily conducted away. Experience in the AFRPL pilot scrubber (Section 4), however, has shown static electricity to be very probable.

Use of grounded conducting (metal) materials for the scrubber walls ensures that sparking will not occur no matter what the charge or resistivity of the particles may be. The chance of sparking between particles is very remote because the particles carry so little charge and are usually like-charged anyway. The use of non-conducting scrubber wall material may allow static electricity to build up enough on the wall to cause sparking. This chance of sparking should be reduced by wetting the walls, which would normally occur in a wet scrubber.

Controlled Afterburning -

The final means of reducing the possibility of combustion of fuel gases in the scrubber is to purposely burn these gases under controlled conditions. The use of after-burners would require consideration of the following factors:

1. Problem of injecting air or oxygen into the hot, fast rocket exhaust stream.
2. Problem of obtaining adequate mixing of the fuel gases and the oxygen to ensure complete combustion.
3. Problem of the increase in flow enthalpy (above the already extremely high value of the rocket exhaust) due to the after-burning.

Since the purpose of the after-burning is to eliminate the possibility of unwanted combustion in the scrubber, the afterburner would have to be located upstream of the low velocity regions in the scrubber where unwanted combustion is most likely to cause explosions. In a wet scrubber system the air injection apparatus would be best located just downstream of the water injectors because the flow would be cool enough there to permit stable combustion. An additional bank of water injectors would then have to be used after the after-burning region to cool the gas, reduce the volume, and slow the flow again. The mixing duct portion of the scrubber would necessarily be longer.

Equilibrium calculations - To make the preliminary calculations simple, the processes were assumed to occur at one atmosphere pressure and achieve chemical equilibrium. The only reactions of importance were:

$$CO + \tfrac{1}{2} O_2 \rightarrow CO_2$$

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$

There are about twenty-five reactions of importance kinetically in CO/H_2/air systems according to Edelmen et al. (1975). However, these reactions need only be considered when determining small amounts (parts per million) of various reaction products, where we are interested in the major products, measured in parts per hundred (percent).

The computer program described in Appendix "A" was run for different amounts of injected air. The effect on velocity for the closed duct quencher, using the same parameters as before is shown in Figure 39.

The amount of air required for complete combustion of the H_2 and CO, for a typical composite propellant, is found from the following equation:

$$\frac{m_{air}}{m_R} = 11.5 \frac{m_C}{m_R} + 34.5 \left(\frac{m_H}{m_R} - \frac{1}{8} \frac{m_O}{m_R} \right) \qquad (31)$$

where the subscripts refer to:

air - air
R - total rocket
C - carbon (in CO)
H - hydrogen (H_2)
O - oxygen (in CO)

From Table 1 for the composite propellant, this equation reduces to:

$$R_a = \frac{m_{air}}{m_R} = 1.15 \qquad (32)$$

This ratio represents an extremely high volume flow rate of air.

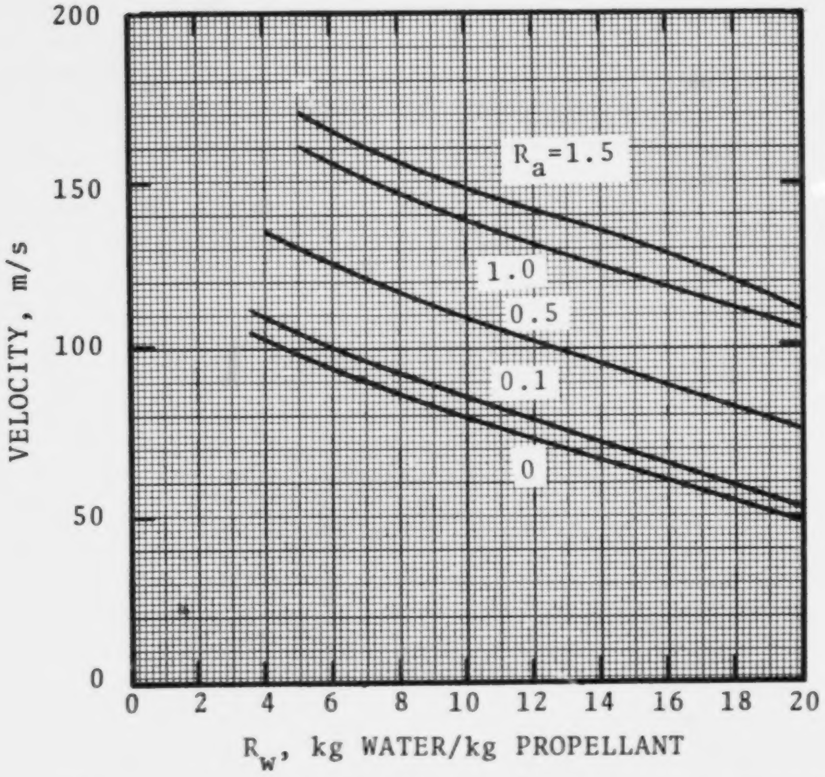


Figure 39. Effect of entrained air on equilibrium velocity.

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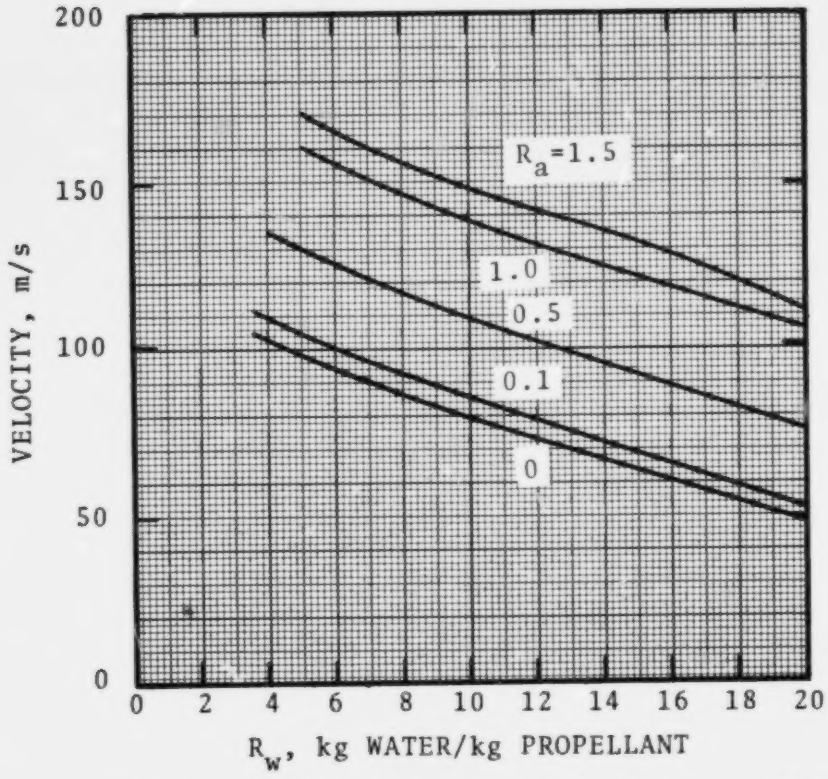


Figure 39. Effect of entrained air on equilibrium velocity.

The other variables such as temperature and pressure are affected also, but not as drastically as velocity. The velocity is increased 74% at $R_w = 10$ from the 10% air ratio of the stoichiometric air ratio (115%). Thus, if a 115% mass ratio of air to rocket propellant were used the cross sectional area of the scrubber would have to be increased 74%, in order to keep the velocity below about 100 m/s. The blowers and related equipment would also increase the complexity and cost of the system.

Conclusions

Afterburning is practically unavoidable either within the scrubber system or at the exit. The addition of enough air to completely burn the fuel gases (CO and H_2) within the quencher is too expensive an alternative. The assumption that a 10% mass ratio of air to rocket propellant will be entrained and burned has some basis in ejector theory. Because of static electricity or local hot spots combustion will likely occur where the exhaust gases contact and mix with air at the exit of the scrubber system. The scrubber must be so designed that pockets of combustible gases cannot form in the system and the system exit region must be relatively unaffected by afterburning in close proximity.

PERFORMANCE REQUIREMENTS

The primary performance requirement of the scrubber system is the removal of hydrogen chloride gas with the efficiency specified in Section 3. Although collection of aluminum oxide particulates is not necessary their removal efficiency can be predicted.

Number of Transfer Units for Gas Absorption

Both HCl and HF are extremely soluble in water so their absorption rate is gas-phase controlled. Consequently, the number of overall gas phase transfer units for hydrogen chloride or hydrogen fluoride gas absorption in an aqueous solution of a base is:

$$N_{OG} = -\ln\left(1 - \frac{E_R}{100}\right) \qquad (33)$$

where N_{OG} = number of transfer units (NTU)
E_R = required efficiency, %

Thus, for an efficiency of 99.6%, 5.52 transfer units are required.

Particulate Removal Efficiency

Since particulate removal is not a primary objective a detailed analysis of removal efficiency will not be presented. A recent discussion of the latest performance prediction techniques can be found in Calvert, et al (1972) and Yung, et al (1976). The "Scrubber Handbook" by Calvert, et al covers all types of scrubbers. Yung presents prediction equations for venturi scrubbers which can be adapted to a gas-atomized rocket scrubber in which category the quencher falls.

A typical operating condition for the rocket quencher/scrubber would be a liquid to rocket mass flow rate of ten ($R_w = 10$) and an air inbleed mass ratio of 1/10 ($R_a = 0.1$) as discussed previously in this chapter. The corresponding velocity and Q_L/Q_G are 84 m/s and 0.015 m^3/m^3, respectively. The mass median diameter of particulates is usually between

2 and 10 μm with a geometric standard deviation of about two.

Using Yung's model and the assumptions, operating conditions, and a mass median particle diameter of 5 μmA an overall efficiency of particulate removal of greater than 99.9% is predicted. This figure would be slightly smaller for smaller mass median diameters. The 50% efficiency size (cut diameter), based on the operating conditions is about 0.33 μmA, so the high efficiency would remain so long as the mass median diameter were greater than about 2 μmA. For alumina particles with a density of about 3.7 g/cm^3 the aerodynamic diameter is approximately twice the actual (physical) diameter for diameters above 1 μm.

CONVENTIONAL SCRUBBER DESIGN

In Section 5 potentially suitable designs were discussed. Since gas absorption was the primary objective, a spray packed column, or plate column type of device would be the most practical choice. Of the spray types the gas-atomized type seemed to be the cheapest since energy was available in the gas stream to provide atomization of the liquid at high relative velocity.

In this subsection the scrubber types are narrowed down to one type on the basis of economic considerations. Preliminary cost estimates of the three types show the gas atomized spray scrubber to be the least costly. A detailed process design is then made for the spray scrubber which primarily involves determining the length required for the mass transfer to take place.

Preliminary Sizing of Spray and Column Scrubbers

Preliminary sizing for cost comparison purposes is based on the large, 2 meganewton (450,000 lbf) thrust, rocket. The scrubber has to operate on the gas leaving the quencher. A gas velocity of 100 m/s was selected as reasonable as a basis for sizing the scrubber. The following table summarizes the flow conditions:

TABLE 13. SCRUBBER INLET CONDITIONS FOR PRELIMINARY SIZING

	Metric	English
Volume flow rate	5,000 Am^3/s	10.6 x 10^{6}ACFM
Gas density	0.53 kg/m^3	0.033 lbm/ft^3

Although these conditions correspond to a quench water ratio, R_w, of 5.6 kg water/kg propellant, which is a little above the minimum required for quenching only, we assume that no HCl has been absorbed in the quencher water.

Spray Scrubber Diameter -

The gas-atomized spray scrubber is mechanically the same as quencher. Operating equations are the same, so that the duct diameter is as previously stated:

$$D_c = \left(\frac{4}{\pi} \frac{\text{Thrust,N}}{40{,}000}\right)^{\frac{1}{2}} \tag{34}$$

Plate Column Diameter -

Calvert et al. (1972) present an equation for plate column diameter based on the allowable superficial gas velocity. The allowable velocity is based on empirical correlations for the onset of priming and/or entrainment of the liquid. The equation for column diameter is:

$$D_c = \left[\frac{4\ Q_G}{\pi\ a}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}} \tag{35}$$

where "a" is an empirical constant with dimensions of velocity. This empirical constant is given in the following table:

TABLE 14. EMPIRICAL CONSTANTS FOR EQUATION (35)

Type of Plate Column	a, m/s
Bubble Cap Tray	0.043
Sieve Tray	0.057
Valve Tray	0.072

Packed Column Diameter -

Packed column diameter can also be calculated by a method presented in Calvert et al. (1972). The allowable velocity is limited by the onset of flooding and the design superficial velocity is usually set at about 75% of the flooding velocity. This flooding velocity is available from charts given in Calvert et al. (1972) or section 4 of Perry & Chilton (1973). The flooding velocity depends on the type and size of the packing. An average "packing factor" for 5 cm diameter packing material is about 160 m^2/m^3. The charts for flooding velocity have "x" and "y" axes which are related to column diameter, gas mass flow rate and liquid mass flow rate for the present conditions by:

$$x = 0.023 \frac{m_L}{m_G} \tag{36}$$

$$y = 0.050 \frac{m_G^2}{D_c^4} \tag{37}$$

Comparison of Diameters -

For the 2 meganewton (450,000 lbf) thrust rocket and condition described in Table 13 the following table compares diameters:

TABLE 15. COMPARISON OF SCRUBBER DIAMETERS

<table>
<tr><th></th><th colspan="2">Diameter, m</th></tr>
<tr><th>Type</th><th>L/G = 1 ℓ/m³</th><th>L/G = 2 ℓ/m³</th></tr>
<tr><td>Gas Atomized Spray</td><td colspan="2">8.0</td></tr>
<tr><td>Bubble Cap Plate</td><td colspan="2">58.4</td></tr>
<tr><td>Sieve Plate</td><td colspan="2">50.7</td></tr>
<tr><td>Valve Plate</td><td colspan="2">45.1</td></tr>
<tr><td>5 cm Packing</td><td>43.8</td><td>46.0</td></tr>
</table>

Spray Scrubber Length -

The length required will be detailed later in this section. It will be shown that only a few meters are required for mass transfer. For comparison purposes we can assume that 5 meters is adequate.

Plate Column Height -

To make a preliminary performance estimate for a system of this kind one can assume a plate efficiency of about 75%.

Since 5.5 transfer units are required a total of 8 plates are needed. The plate spacing in industrial usage is about 0.5 meters, so a height of about 4 meters is needed. Including ends, a total of about 5 meters would be adequate.

Packed Column Height -

As a rough rule the height of a transfer unit is between 0.5 and 1 meter. Using the mid-range value of 0.75 meter, a total column height of about 4.2 meters is required. Adding ends, about 5 meters would be the total requirement.

Auxiliaries -

Auxiliary equipment includes the caustic tank, pumps, piping, quencher, sewer, and drying pond. These items are common to all the scrubber types and need not be costed for comparison purposes. It is assumed that the spray scrubber needs a low velocity entrainment separator, while the other types can operate at low enough velocities that the amount of entrainment they generate is acceptable for discharge.

It will be seen that even with this disadvantage the gas-atomized spray is cheaper than the others so the foregoing assumption is acceptable. Since so much power is available to the system from the rocket exhaust a cyclone type separator, as described later, is cheapest for the gas-atomized spray scrubber. For the 2 MN rocket the entrainment separator would consist of 7 cyclones, each 8 m in diameter and 24 m high.

Preliminary Cost Estimates for Spray and Column Scrubbers

Cost estimates were made based on a number of sources, including Chilton (1960), Calvert (1968), Peters and Timmerhaus (1968), Popper (1970), Guthrie (1974) and Lee Saylor (1976). A consensus summary of the cost estimates for the 2 MN rocket is presented in Table 16 . The first three figures presented are for the plate or packed column scrubbers while the last figure represents the ducted spray. These figures are at best rough estimates and are presented for comparative studies only. There are two reasons for this; first the designs for each process can at best be considered conceptual. From a comparative economic standpoint this is not serious since the overall processes evaluated are essentially similar and differ

TABLE 16. CAPITAL COST ESTIMATES FOR LARGE ROCKET SCRUBBER (in millions of dollars, mid-1976)

Scrubber Type	Sieve Plate	Bubble Plate	Packed Plate	Spray & Cyclone
Scrubber Cost	13.7	15.5	12.4	2.2
Auxiliaries*	2.7	2.7	2.7	2.7
Total	16.4	18.2	15.1	4.9

*Auxiliaries include: cooling duct, deflector, waste treatment, piping, caustic facilities, and sewerage.

only in the type of scrubber being used for each system. The second reason which limits application of the figures for absolute purposes is the nature of the job being estimated. The rocket scrubber process is unique from the viewpoint that no systems are in current operation from which to base economic values.

In large part, dollar values have been derived from basic cost estimation fundamentals. This can often give considerable errors of magnitude in the estimates made for each process component. In general these errors tend to be smoothed out on the summation of the item costs for total process cost purposes. In consideration of these limitations the figures presented for the capital cost estimates may be taken as plus or minus 30%.

The estimates may therefore be considered significant because they give positive information regarding the selection of the final process design.

The figures presented are total complete project costs for a mid-1976 base. Note that the total process costs have been split into two parts, namely for the scrubbing section and for the auxiliaries. "Auxiliaries" in this case refers to the cooling duct, deflector, waste treatment, piping, caustic facilities and sewerage. The auxiliaries costs are identical for each process and have been separated from the total cost figure to highlight the effect of scrubber costs on the project.

Where materials of construction need to be specified, carbon steel 0.64 cm (0.25 in) thick is used. The scrubber sizes in some cases were so large that estimating techniques were difficult. In these cases costs are based on a number of smaller diameter units with an equivalent total flow area.

It is evident that the ducted spray scrubbing system is superior to the other units from the capital cost standpoint. At $4.9 million its cost is approximately one-third of its closest rival, the packed column.

Even allowing for the magnitudes of error inherent in the costing process there is sufficient spread in the capital cost numbers to conclude that the spray is the most promising device for cleaning the rocket exhaust gases.

Process Design for Spray Scrubbing

The process design for the gas-atomized spray scrubber involves specification of the liquid flow rate, liquid composition, duct cross-section, and mass transfer length. The equilibrium conditions, assuming an infinite length scrubber, are calculated with the same equations as were used for the quencher. There is, in fact, no difference between the quencher and the gas-atomized spray scrubber other than that more mass transfer can occur in the scrubber. Thus, the only new design equations to be presented will concern the mass transfer.

Equilibrium Conditions -

For the specification of liquid flow rate, liquid composition, and duct cross-section the quencher and scrubber can be considered one unit. The liquid supply would come from one source rather than two to reduce costs. The duct would be one section of uniform area. The liquid supply would, however, have to be injected at two different distances from the duct entrance since the prediction of the gas-atomized drop size is very difficult based on injection into a hot, supersonic stream. This two staged liquid injection will not affect equilibrium calculations. The conservation equations were described in the subsection on quenching equilibrium. The air entrainment rate is assumed to be 0.1 kg air/kg propellant as for the previous quencher calculations.

The criterion for quenching design was to provide a saturated gas at about 100 m/s (328 ft/s) velocity, such as commonly occurs in a venturi scrubber using an economic tradeoff between liquid flow rate and duct area. The duct area selected was:

$$A_D = \frac{\text{Thrust}}{40,000}\ ,\ \text{m}^2 \qquad (38)$$

where the thrust is in newtons. This criterion is valid for the scrubber section also. The quench water mass flow rate required is about 5 times the rocket mass flow rate based on the figures previously presented. The required scrubber liquid flow rate will be developed in the mass transfer analysis.

The scrubber liquid composition should be a basic solution so that evaporation of the liquid after it leaves the scrubber will not cause vaporization of the acid gases and to reduce corrosion. The very high solubilities of HCl and HF in water minimize the need for a basic solution to improve mass transfer rate. Table 17 shows the costs of four commonly used basic chemicals, based on vendors' quotes for mid-1977 in the Los Angeles area.

TABLE 17. BASIC CHEMICAL COSTS, MID-1977.

Chemical	Cost per 1,000 kg	Cost for 10 Large Rockets (99,150 kg HCl)
$Ca(OH)_2$	$105	$10,570
NaOH	528	57,430
KOH	655	99,750
Na_2CO_3	148	21,340

Besides cost difference these four chemicals have different solubilities, so that slurry moving equipment and piping are required for some. The solubilities are (based on Weast, 1971):

TABLE 18. CHEMICAL SOLUBILITIES

Chemical	Solubility, g/100 cm³ solution	
	30°C	100°C
$Ca(OH)_2$	0.153	0.077
NaOH	119	347
KOH	126	178
Na_2CO_3	38.8	45.5

Garrett et al (1972) objected to $Ca(OH)_2$ because of the insolubility of calcium fluoride, CaF_2, but that would seem to be a minor point for the solid rocket. So much insoluble aluminum oxide (Al_2O_3) will be present that the CaF_2 would be insignificant. For the solid rocket the entrainment separator and plumbing must be able to handle an appreciable amount of undissolved solids.

The cost of the systems required to handle either a slurry of $Ca(OH)_2$ or a solution of Na_2CO_3 must be weighed against the chemical costs. This tradeoff depends primarily on the use frequency and projected system lifetime. Based on frequency of 10 tests per year and a 10-year life Na_2CO_3 is recommended.

The minimum concentration of the base should be a stoichiometric balance with the amount of HCl and HF present. The maximum concentration should be the smaller of twice stoichiometric or 50% by mass, which is about the highest slurry concentration that can be pumped and piped economically. The stoichiometric mass flow ratio with HCl is:

$$\frac{\text{g } Na_2CO_3}{\text{g HCl}} = \frac{106}{2(36.46)} \approx 1.45 \qquad (39)$$

For the composite propellant rocket the amount of HCl emitted is 17.1 mole %, or 21.4 mass % of the total rocket exhaust. Thus, the stoichiometric amount of Na_2CO_3 is:

$$m_{Base,\ stoich} = 0.31\ m_r \qquad (40)$$

and the mass concentration of Na_2CO_3 is:

$$C_{Base,\ stoich} = \frac{0.31}{R_s} \qquad (41)$$

where "R_s" is the scrubber liquid to rocket mass flow rate ratio. At double the stoichiometric amount of base a 50% concentration corresponds to $R_s = 0.81$, which is a much smaller ratio than will be required for the scrubber.

Equilibrium Mass Transfer -

HCl and HF produce a temperature increase when dissolved in water and this causes their solubilities to decrease. While it is possible to account for the heat effect on the mass transfer rate, it requires a complex computation. For simplicity it is assumed that the interfacial liquid temperature is 100°C, which is about the maximum possible. This is a conservative assumption which is later shown to be acceptable. The equilibrium line on Figure 40 is based on data in section 3 of Perry & Chilton (1973) for 100°C.

For co-current physical absorption (i.e., no base used) the operating line shown in Figure 40 is based on the following:

Inlet: $x_{in} = 0.0$

$y_{in} = 0.024$

Outlet: $y_{out} = (0.004)\ y_{in} = 9.6 \times 10^{-5}$

where x = mole fraction HCl in liquid

y = mole fraction HCl in gas

and "y_{in}" is based on figures presented in the quencher analysis

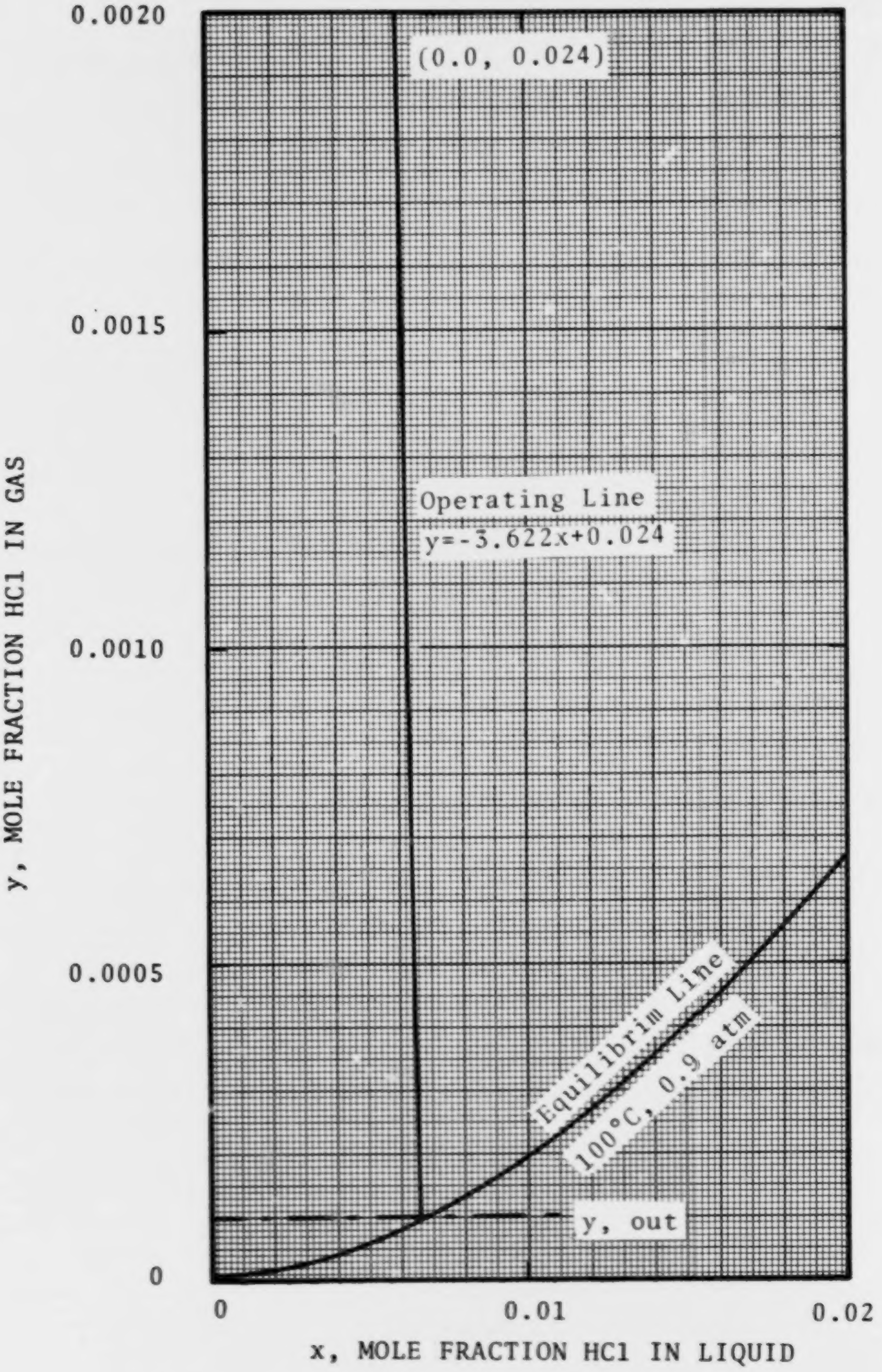


Figure 40. Physical absorption of HCl.

section for $R_w \approx 5.6$, but assuming no HCl absorption in quencher. The intersection of "y_{out}" with the equilibrium line determines "x_{out}":

$$x_{out} = 0.066$$

The slope of the operating line is the minimum liquid-to-gas mole ratio:

$$\left(\frac{n_L}{n_G}\right)_{min} = 3.62 \text{ moles liquid/moles gas}$$

Based on the figures presented in the section on quencher analysis, the liquid-to-gas mole ratio has been calculated as a function of the scrubber liquid flow rate and is shown in Figure 41 . The zero point on this figure was taken at a quencher "R_w" of 5.6, so that the total system minimum water requirement for a scrubber liquid-to-gas mole ratio of 3.62 is as follows:

$$R_T \approx 5.6 + 8.8 = 14.4 \text{ kg water/kg propellant}$$

Since the phase equilibrium was based on a conservative 100°C, an $R_T = 15$ should represent an adequate operating flow rate of water. The mass transfer efficiency for a basic solution would be better than that for physical absorption in water. The mass concentration of Na_2CO_3, based on a double stiochiometric ratio and equation (41) should be about 4% in the total liquid.

Mass transfer coefficient - In a steady state process of absorption, the rate of mass transfer through the gas film may be expressed by:

$$N = k_G (p_G - p_i) \qquad (42)$$

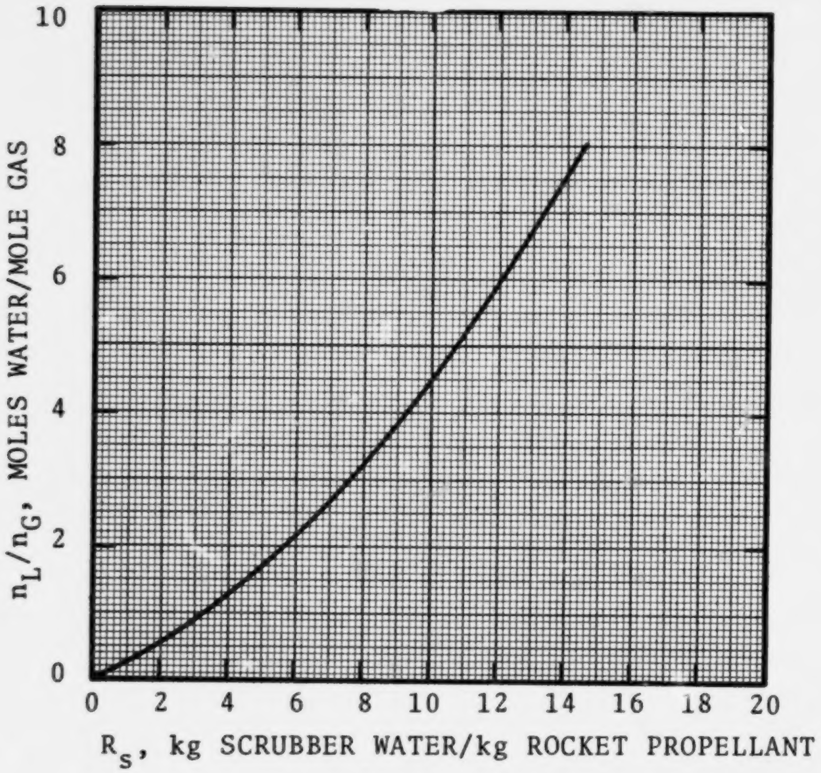


Figure 41. Liquid to gas ratio in scrubber.

where "N" is the molar flux of transferring component (kgmol/s-m^2), "k_G" is the gas phase mass transfer coefficient based on conditions at the interface (kgmol/s-m^2 atm) and "p_g" and "p_i" represent the partial pressure of the diffusing component in the bulk of the gas and the interface, respectively. It is normally more convenient to rewrite the rate expression in terms of the overall gas phase coefficient "K_G" based on equilibrium conditions, i.e.:

$$N = K_G \ (p_G - p_e) \tag{43}$$

where "p_e" is the equilibrium partial pressure.

If the mass transfer process is gas phase controlled, i.e., $k_G \approx K_G$ replacement of the film coefficient with the overall coefficient to express the mass transfer rate is justified. Calvert (1968) suggests the system to be gas phase controlled if the Henry's Law constant is less than 0.2 atm/(kgmol/m^3), and liquid phase controlled if Henry's Law constant is greater than 200 atm/(kgmol/m^3). In our case of dilute HCl at 0.9 atm pressure the lower value corresponds to $y/x=0.004$. The Henry's Law constant corresponds to the slope of the "equilibrium line" at the operating point. This slope is $y/x=0.024$, based on Figure 40, which is much closer to the gas phase control criterion than to the liquid phase control criterion.

Gas film transfer coefficient (k_G) - Gas film transfer coefficient (k_G) is calculated using the semi-theoretical equation of Frössling in Calvert et al. (1972):

$$\frac{k_{G_z} \ R_G \ T \ d_d}{D_G} = 2. + 0.552 \ Re_z^{1/2} \ Sc^{1/3} \tag{44}$$

where $Re = \dfrac{d_d \ u_r \ \rho}{\mu_G}$ = Reynolds number

$Sc = \dfrac{\mu_g}{\rho_G \ D_G}$ = Schmidt number

R_G = ideal gas law constant
T = absolute temperature, °K
d_d = drop diameter, m
D_G = gas phase diffusivity , m^2/s
u_r = relative velocity between drop and gas, m/s
ρ_G = density, kg/m^3
μ_G = viscosity, kg/m-s

Subscript "z" refers to point conditions at distance "z" from the point of atomization

The effect of drop velocity on the mass transfer coefficient is apparent in the above expression. For the rocket scrubber, this implies constantly changing values for "k_g" with time (or drop travel distance) as the atomized liquor accelerates along the plume path. This point will be returned to later in discussing the scrubber length required to complete the necessary mass transfer.

Atomized drop diameter, d_d, was estimated from the Nukiyama and Tanasawa equation in Calvert et al. (1972):

$$d_d\,(\text{cm}) = \frac{0.50}{u_G} + 91.8\left(\frac{Q_L}{Q_G}\right)^{1.5} \tag{45}$$

at standard conditions

where Q_L = liquor flow rate, m^3/s
Q_G = gas flow rate, m^3/s
u_G = gas flow rate, m/s

The instantaneous drop velocities were computed from the equations of motion for drops accelerated into a gas stream according to Dallavale (1948):

$$\frac{d\,u_{d_x}}{dt} = \frac{\rho_G\ C_R\,\frac{\pi}{4}\,d_d^2\,u_r\,u_{d_x}}{2\,m} \tag{46}$$

$$\frac{d\,u_{d_y}}{dt} = g\left(\frac{\rho_G - \rho_d}{\rho_d}\right) - \left(\frac{\rho_g\, C_R\, \frac{\pi}{4}\, d_d^2\, u_r\, u_{d_y}}{2\,m}\right) \tag{47}$$

where u_{d_x} = the point horizontal component of the absolute drop velocity (u_r) at a distance, z, from the point of atomization (m/s)

u_{d_y} = the point vertical component of the absolute drop velocity (u_r) at a distance, z, from the point of atomization (m/s)

C_R = the coefficient of resistance, dimensionless

m = the mass of drop, kg

Liquid film transfer coefficient (k_L) - The liquid film coefficient for mass transfer to drops was calculated by the equation in Calvert et al. (1972):

$$k_L = 2\left(\frac{D_G}{\pi\theta}\right)^{1/2} \tag{48}$$

where k_L = the liquid film transfer coefficient based on conditions at the interface (kgmol/s-m^2)/(kgmol/m^3)

θ = the contact time, s

The time of exposure of the drop to the gas stream, θ, was taken as the time required to accelerate the drop to 1.0 meter from the trajectory starting point. The instantaneous value for "k_G" was also taken at this point to compute the ratio k_L/k_G. Selection of the 1.0 meter travel length is considered conservative since drop collisions would be expected in shorter lengths.

Scrubber length - The procedure used to calculate the scrubber length is described on the following page.

For the co-current flow conditions found in the gas-atomized spray scrubber, the required absorber length, z, may be expressed by the relationship:

$$\frac{P}{n_G}\int_o^z K_G\ a\ dz = \frac{\left(y_{out}-y_{in}\right)}{\left(y-y_e\right)_{lm}} \tag{49}$$

where y_{out} & y_{in} = the mol fractions of HCl in the gas phase at the scrubbing section outlet and inlet respectively

y_e = the mol fraction in the gas phase at equilibrium with the liquor

$\left(y-y_e\right)_{lm}$ = the logarithmic mean value of $\left(y-y_e\right)$ for the inlet and outlet conditions

This assumes a linear equilibrium relationship over the concentration range of interest. As can be seen in Figure 40 this is a justified approximation over the range from "y_{in}" to "y_{out}".

The expression on the right-hand side of equation (49) is commonly referred to as the number of transfer units required for the operation (N_{OG}).

For the present HCl absorption conditions, the number of transfer units required for the process is 5.52. The gas mole flow rate, n_G, may be expressed in terms of linear gas flow rate, u_G, according to the following expression:

$$n_G = \frac{\left(\rho_G\ u_G\right)}{M} \tag{50}$$

where M = the molecular weight of gas

For ρ_G=0.53 kg/m³ and P=0.9 atm, equation (49) reduces to:

$$\int_o^z K_G\ a\ dz = 0.2\ u_G \tag{51}$$

Both "k_G" and "a" vary with position along the drop trajectory. Moreover, it has been shown that for the case of gas phase limiting, k_G, the film coefficient, may be used to represent K_G, the overall gas coefficient. Thus, equation (51) may be written:

$$K_{G_z} = \frac{D_G}{R_G\ T\ d} = 2 + 0.552\ Re_z^{\frac{1}{2}}\ Sc^{\frac{1}{3}} \qquad (52)$$

The mass transfer area, a, may be related by the following expression:

$$a_z = \frac{6}{d}\left(\frac{Q_L}{Q_G}\right)\left(\frac{u_G}{u_{d_z}}\right) \qquad (53)$$

Equations (45), (46), (47), (52), and (53) afford a solution to the mass transfer length as a function of gas velocity as expressed by equation (51). This is best accomplished by computer programming.

The procedure adopted was to obtain an expression for the product of "$K_G a$" as a function of drop travel distance, z, for a number of gas velocities ranging from 10 m/s to 100 m/s. The program was set up to compute the drop size according to equation (45). Instantaneous drop velocities, u_{d_x} and u_{d_y}, were then calculated from equations (46) and (47) using the method of finite differences for successive increments of time, Δt. Knowing the drop velocity at each time interval, it is possible to compute instantaneous values for "K_G" and "a" from equations (52) and (53), respectively.

The next stage was to obtain an expression for the product, $K_G a$, as a function of drop travel, z. It was found that the results could be expressed by the form:

$$K_G a = C_1 z^{C_2} \qquad (54)$$

where C_1 and C_2 are constants.

The expressions obtained for each gas velocity were found to represent the calculated data with an exceptionally high index of fit (approximately 1.0 in all cases).

Reduction of the expressions for "K_ga" to the form presented in equation (54) simplifies calculation of the drop travel required for mass transfer. Thus, substituting the expression for "K_Ga" in equation (51) gives a simplified expression for the transfer length required for mass transfer:

$$\int_0^z C_1(z)^{C_2}\,dz = 0.2\,u_G \qquad (55)$$

Note that the constants "C_1" and "C_2" are independent of mass transfer length, z. However, they are dependent on gas velocity, u_G.

Using the expression presented in equation (55) it is now possible to compute the plume transfer length as a function of gas velocity. This is shown in Figure 42.

The important point brought out in Figure 42 is the small plume length required for mass transfer for the practical gas flow rates anticipated for the rocket. Even at the exceptionally low velocity of 10 m/s, travel length is only 3.5 meters. Moreover, for velocities 30 m/s to 100 m/s the required length is relatively consistent at 1.75 m.

What this implies in practical terms for the rocket study is that the plume length required for mass transfer is not the critical design parameter. The simplifying assumptions which were made in the computation are acceptable because they do not have a significant influence on the required contact length for mass transfer. More important is the length required for momentum and heat transfer in slowing down the gases to a velocity suitable for particle and drop separation and cooling the hot gases to the scrubbing liquid boiling point.

Conclusions - The plume length required to complete the mass transfer of HCl gas to scrubbing liquid has shown that a distance of 3.0 meters is adequate to handle all practical gas velocities likely to be encountered in designing the rocket scrubber.

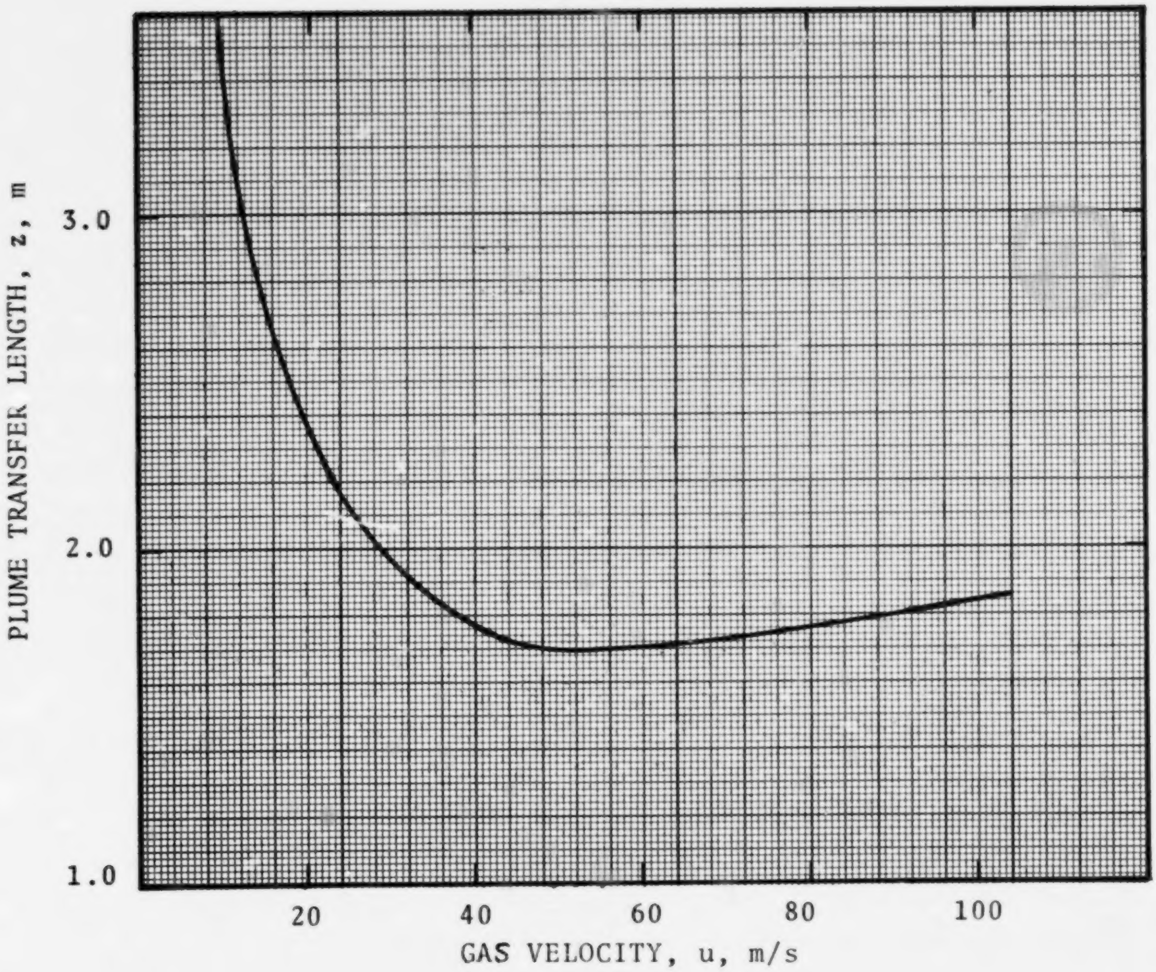


Figure 42. Effect of gas velocity on plume length required for HCl mass transfer to scrubbing liquor at 0.9 atm.

Coupling Effects between Scrubber and Rocket

From the point of view of the rocket test engineer it is very important that the exhaust scrubber not affect the rocket performance. The effects of the scrubber on the rocket were discussed briefly in Section 2 and the first part of this section (6). It was pointed out that because of the supersonic nature of the rocket exhaust the scrubber could not affect the rocket chamber conditions of pressure, temperature, and and propellant mass flow rate during normal operation. It is possible that the pressure on the exterior of the rocket nozzle expansion cone and consequently the measured thrust will be affected by the scrubber.

As discussed in the subsection on definition of the process the rocket nozzle acts as an ejector pump to entrain air into the scrubber. In order to limit the amount of entrained air the gap between the nozzle exit and the scrubber entrance should be small. The smaller the gap the higher the velocity of the entrained air past the nozzle exit. And, according to Bernoulli's equation, the lower the static pressure on the outside of the nozzle exit. An estimate of the amount this ambient pressure is decreased based on the assumed mass influx of air of 10% of the rocket mass and a co-planar arrangement yields the equation: (Bernoulli's equation using parameters of the large rocket.)

$$\frac{p_a'}{p_a} = 1 - \frac{0.0116}{(f^2-1)^2} \qquad (56)$$

where p_a' = reduced ambient pressure
p_a = ambient pressure
f = ratio of scrubber entrance diameter to rocket nozzle exit diameter

For a 10% pressure reduction $f = 1.16$ which for the large (2MN) rocket means that the difference in radii (gap) between the scrubber entrance and the nozzle exit would be 11 cm (4.4 in).

This lowered pressure (Pa) affects the thrust as seen in the thrust coefficient equations for an ideal rocket from Hill and Peterson (1965):

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\left[1-\left(\frac{p_e}{p_o}\right)^{(\gamma-1)/\gamma}\right]} + \left(\frac{p_e-p_a}{p_o}\right)\varepsilon \qquad (57)$$

where γ = ratio of specific heats
p_e = exit pressure, N/m^2
p_o = chamber pressure, N/m^2
p_a = ambient pressure, N/m^2
ε = nozzle area expansion ratio

and

$$\varepsilon = \frac{\left[\frac{2}{\gamma+1}\left(\frac{p_e}{p_o}\right)^{\frac{1-\gamma}{\gamma}}\right]^{\frac{\gamma+1}{2(\gamma-1)}}}{\left\{\frac{2}{\gamma-1}\left[\left(\frac{p_e}{p_o}\right)^{\frac{1-\gamma}{\gamma}}-1\right]\right\}^{\frac{1}{2}}} \qquad (58)$$

The obvious effect of the reduced ambient pressure is in the reduction of the term in equation (57):

$$\left(\frac{p_a}{p_o}\right)\varepsilon$$

which increases the thrust coefficient, C_F. The other effect is that, because of the reduced pressure on the nozzle outside surface the exit pressure, p_e, is effectively increased. Put another way, the net pressure force acting on the rocket in the direction of the thrust (which creates the thrust) is reduced. This effective exit pressure increase can also be considered an effective nozzle exit area and length decrease. This length decrease would be to the location on the nozzle exterior surface where the pressure was equal to the ambient pressure. This could be determined experimentally by locating static pressure taps at various distances forward from the nozzle exit plane.

To illustrate the effects, equation (57) has been plotted for $\gamma = 1.15$ in Figure 43. An example of the effect of a 50% reduced effective exit area and a 50% reduced ambient pressure is shown. The net effects cancel, so that the thrust coefficient, C_F, is not changed. The 50:50 relationship between reduced effective nozzle area and ambient pressure is strictly for illustrative purposes and would have to be determined experimentally. It should be noted that if the design point were located at a greater than optimum expansion ratio the effects would not cancel and a higher thrust would result.

Conclusion -

For most experimental rockets which are underexpanded the effect of the scrubber on thrust should be small, e.g. less than 5%. This coupling effect should not be considered the only impact that a scrubber has on a rocket test. Two examples: 1. Thrust vector control tests - The rocket nozzle is moved side to side various degrees of arc and it must not touch the scrubber. The scrubber entrance would also have to be extra large to capture the exhaust when the nozzle is canted to one side. 2. Vertical upward exhaust tests - This configuration would require precise control of the quench and scrubbing liquid shut-down so that parts of the rocket would not be wetted which could cause damage. During start-up the nozzle would have to be sealed to keep the igniter and propellant from getting wet.

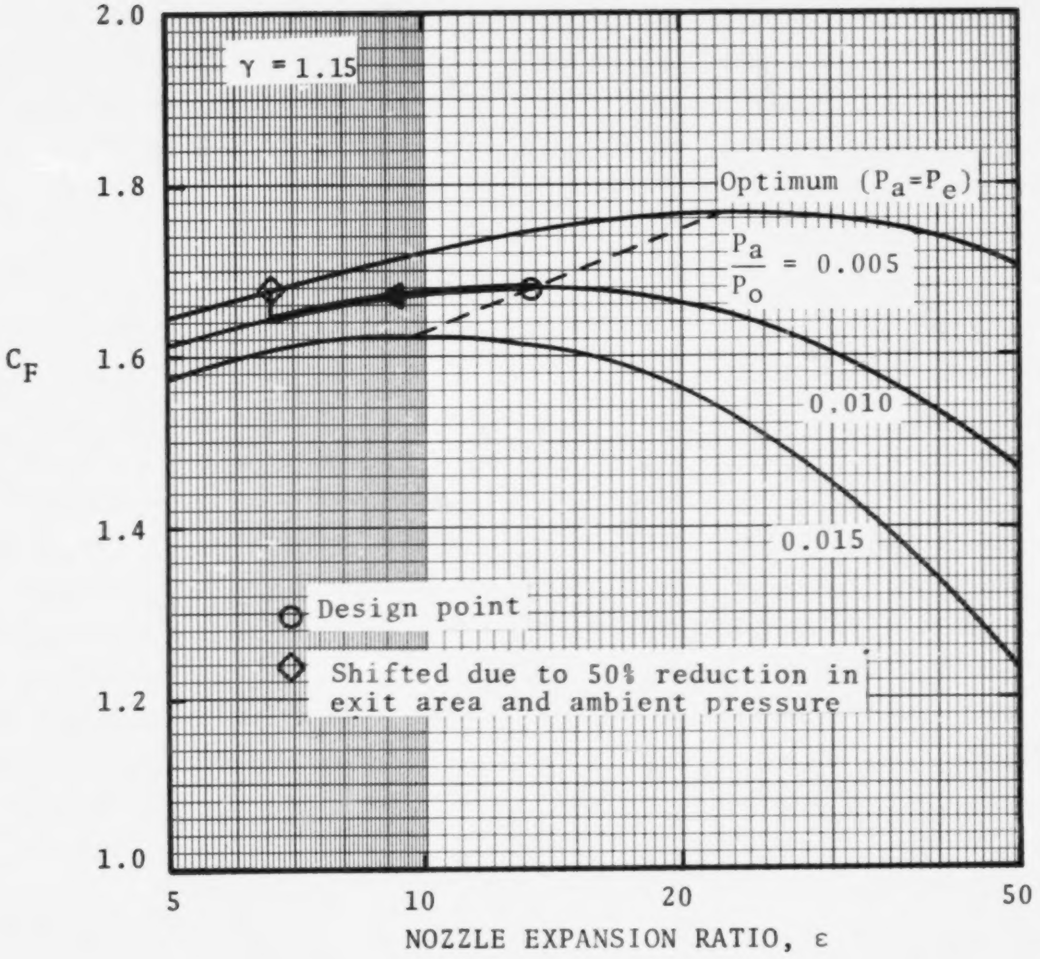


Figure 43. Rocket thrust coefficient.

Design Details

So far only the overall process has been considered. In this subsection the various details of the design will be discussed. Following this discussion of design details the entrainment separator will be described.

Total Quencher/Scrubber Length -

Garrett, et al. (1972) and the experimental results presented in Section 4 suggest that a total length to diameter ratio of 10 is adequate. This is subject to the constraint that the length of the section aft of the scrubber liquid injection point has to be 3 meters (10 ft). A conservative design would be to make the L/D for the quench section 10 and then add a 3 meter spray scrubber section.

In order to keep the length to reasonable values the system should be made of a bundle of small diameter round or rectangular sections as shown in Figure 44.

Quench Liquid Injection -

The radial injector designed by Garrett, et al. (1972) for the pilot scale scrubber was not adequate, as discussed in Section 4. The tips of the injectors burned off and the liquid did not break up the supersonic core. The simple pipe with an angle iron protector as used in the tests in the AFRPL pilot scrubber tests did prove adequate. It is fully described in Section 4. The one improvement to this design would be to coat the angle iron protectors with a trowelable or castable insulation which would increase their life.

Evaporating Pond -

The waste liquid flows by gravity to an evaporating pond. The pond is lined with PVC to prevent seepage of the salt into the water table. The design is based on a 10-year storage of dry material and sufficient area for evaporation. The evaporation rate at AFRPL is about 2.96 m/year and the rainfall averages about 10.4 cm/year. The surface area is based on the volume of liquid waste generated during a test divided by the evaporation

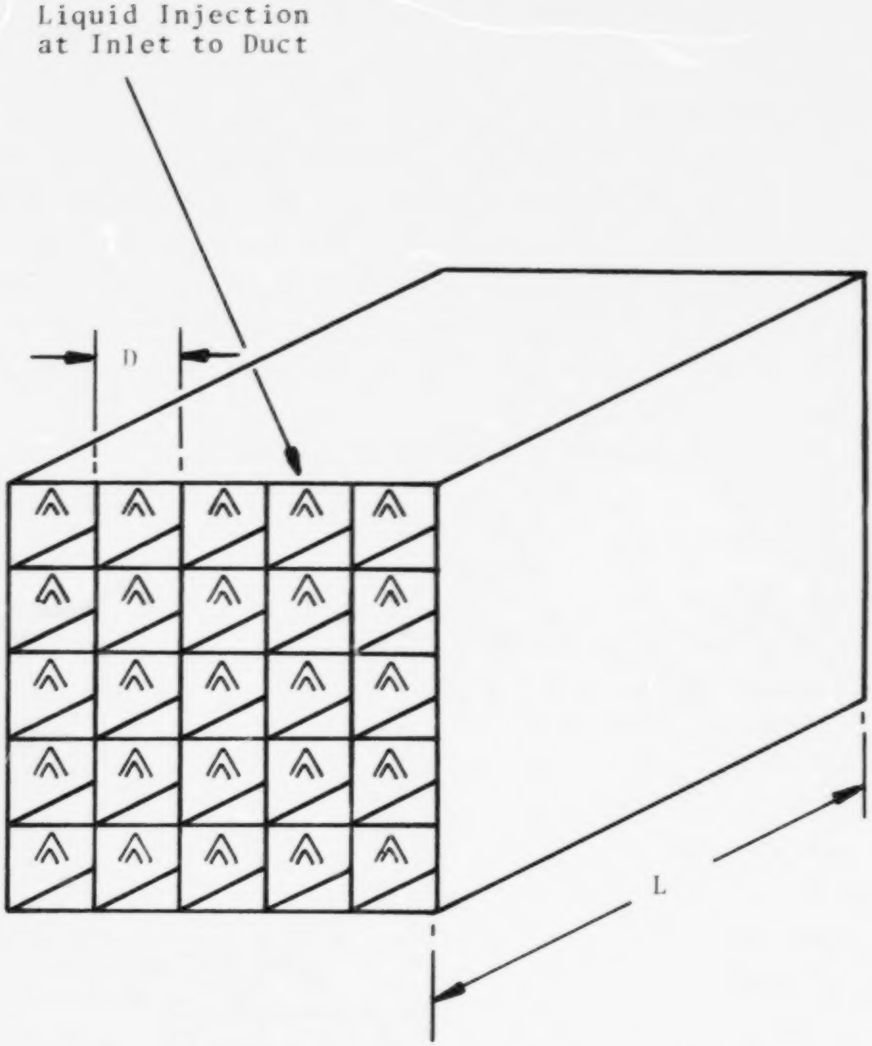

Liquid Injection
at Inlet to Duct
D
L

Figure 44. Sketch of gas-atomized scrubber section.

occurring during the period between tests. The depth is based on the amount of solids expected to build up during the life of the pond or between clean-out periods.

Water Storage Tank -

The tank should be sized to hold twice the amount of water required during a test to allow for misfirings, pump malfunction, and other contingencies. For the 2 MN rocket the volume should be about 1,390 m^3 (49,100 ft^3=367,000 gal).

Piping to Scrubber -

Because of the low frequency of use and the dry climate conventional carbon steel pipe can be used. The pipe should be sized to minimize the line pressure loss, which will depend on the piping length. A few expansion joints will be needed because of the temperature variation in the desert climate.

Piping of Scrubber Waste Liquid -

Because of the solids content and lower available pressure head precast concrete pipe should be used. In many applications an open concrete culvert will be adequate.

Caustic Tank and Mixer -

Depending on topography the caustic tank may or may not be elevated. The size is relatively small and will not significantly effect overall costs whether or not it is elevated. The tank should be sized to hold a 30% by weight solution or suspension of the required base. It should be stainless steel. A pump (or multiple pumps) will be required to inject the concentrated base into the mixer with the fresh water. The mixer need not be powered but should have baffles to create turbulent mixing. The caustic pump will create most of the mixing action.

Materials of Construction -

Because of the low frequency of testing, especially for the large size rockets, carbon steel is adequate for the quencher, scrubber, and entrainment separator. The material should be 0.64 cm (0.25 in) thick to allow for corrosion. If the use is relatively frequent stainless steel could be justified.

Power Requirements -

Very minimal power is required. Unlike other pollutant sources, all the gas moving power is supplied by the source itself. Also, with the use of hilltop or elevated water tanks the liquid is moved by gravity. The water can be pumped to the tanks by natural underground pressure or by low-power small pumps because of the length of time between tests. The major power user is the caustic pump which will use about 0.2 watts per newton of rocket thrust (0.001 HP/lbf). While this is a large amount of power for the large rockets, its duration is so short (1-2 minutes) that the energy usage is slight. Other power users in the system would be the power actuated valves.

Sampling and Analysis -

The discharges from the rocket scrubber have to be monitored in order to determine the amount of pollutants escaping into the atmosphere. Elaborate and expensive instruments for continuous monitoring are either available or can be adapted for use in the rocket scrubber application. These instruments include gas chromatographs, IR and UV spectrophotometers, coulometers and colorimeters. The need for continuous monitoring, however, is not great because the duration of operation is usually only about one minute. Also the operation will be steady and the rocket exhaust is at a constant mass rate for over 90% of the burning time. Thus, because of the short duration and the steady operation, less expensive average sampling can be used. A description of the suggested sampling and analysis methods follows.

Gaseous Emissions - The gaseous pollutants are hydrogen chloride, hydrogen fluoride, carbon monoxide, and possibly, nitrogen oxides.

HCL - Collect by fritted glass absorbers or impingers and analyze solution using a chloride specific ion electrode.

HF - Collect by fritted polypropelene absorbers or impingers and analyze solution using the fluoride specific ion electrode method (see EPA Method 13 B).

CO - Collect a gas sample and analyze by non-dispersive infrared spectrometry (see EPA Method 10).

NO_x - Collect a gas sample in an evacuated flask containing an abosrbing solution. The amount is then determined by colorimetric analysis (see EPA Method 7).

If a mass spectrometer is available the gas could be simply "grab" sampled and taken to the laboratory for analysis.

Water Mist - All the pollutants produced by the rocket (HCl, HF, CO, NO_x, fluoride salts and Al_2O_3 particles) may be found in the water droplets escaping from the mist eliminator. The chemical composition of the mist can be determined by collecting the drops in impingers and analyzing the solution by chemical and specific ion electrode methods.

Solid Particles - The mass loading of the solid particles may be determined by collection on high efficiency filters (see EPA Method 5) and refer to Section 4 for a typical setup. The size distribution is determined by using cascade impactors or multiple filters. The primary solid particulates should be Al_2O_3, but chemical analysis should be made to determine if HCl or HF have been adsorbed on the Al_2O_3 and if any fluoride salts are present.

Waste Water - The waste water should be analyzed to serve as a check on the results of the gas stream analysis.

Two important considerations must be kept in mind when designing instrumentation for the rocket scrubber. The first is that the sampling must be done remotely. Remote sampling requires special flow measuring instrumentation and use of solenoid valves and switches to turn the sampling equipment on and off at times corresponding to the start and end of the motor operation. The second consideration is that the flow from the scrubber exit may be non-uniform and hot due to afterburning. Because of non-uniformity, a number of sampling probes should be used simultaneously. Afterburning will probably ruin any conventional sampling apparatus. The scrubber exit should be designed to provide a region of uniform flow to keep the number of sampling probes required to a minimum and reduce afterburning effects.

Labor and Maintenance -

Construction labor costs are factored into the overall construction costs later in the report. Maintenance of the scrubber consists mainly of a thorough flush and clean water wash of all system components to remove residual caustic or unneutralized HCl. The caustic pumps, especially, should be flushed after each run. Additional maintenance is required for instrumentation set-up and check-out before each test.

Control and Monitoring -

Control of the entire system would be integrated with the main rocket firing control panel as a sub-panel which would initiate the water supply system and caustic release all in a related sequence to the rocket firing. All the valves and motor starters would have to be power actuated so that they can be operated by the control computer. The important flow rates, pressures, and temperatures need to be monitored to determine if the correct process conditions were being met.

Safety -

The use of caustic chemicals in the scrubber liquid requires handling precautions not normally encountered by rocket testing personnel. Standard precautions are available from the manufacturer and consist mainly of care in avoiding contact by splashing of the liquid or by inhaling of the vapors.

The maintenance crew should take precuations when flushing the system to avoid contact with the residuals. These residual solids and liquids may contain unreacted caustic and acid. Flushing with fresh water may also cause heat evolution and in addition to the temperature hazard the heat could cause emission of toxic gases, such as HCl.

Another hazard to the maintenance crew would be pockets of toxic and combustible gases in the system. Time must be allowed for these gases to disperse before entering the system. Depending on how well ventilated a particular portion of the system is the crew may even need to use self-contained breathing apparatus when first entering the system.

CONVENTIONAL SCRUBBER ENTRAINMENT SEPARATION

The conventional rocket scrubber design requires an entrainment separator because the carrier gas is moving at too high a speed to permit quick settling out of the droplets by gravity. The effect of having no entrainment separator would be the deposition of alumina and salts for up to a kilometer aft of the scrubber. This deposition may be tolerable under certain condition unless fluoride salts are present and plant or animal damage may result.

In order to design an entrainment separator the gas conditions, drop size distribution, drop composition, gas loading, and allowable pressure drop must be determined.

Gas Conditions

To serve as a baseline a total injected water mass flow rate to rocket mass flow rate (R_w) of 15 is used. The rate of air bleed (R_a) is assumed to be 0.1 . The gas conditions, using the figures presented in the quencher analysis section are summarized in Table 19.

TABLE 19. . GAS CONDITIONS AT SCRUBBER OUTLET

R_w = 15 kg water/kg propellant

R_a = 0.1 kg air/kg propellant

Q_G = 3,350 m^3/s (large rocket)

u = 67 m/s

ρ_G = 0.54 kg/m^3

Q_L = 10.2 m^3/s liquid water drops*

* assuming no gravity settling or wall catch

Drop Size Distribution

Determination of the distribution of drop sizes is based on the Nukiyama-Tanasawa relation given in equation (45). The result is a Sauter mean drop diameter of about, d_d = 0.016 cm. Assuming a geometric standard deviation of about, $\sigma_g = 2$, and assuming a log-normal distribution, the geometric mass mean diameter is d_{dg} = 0.020 cm based on a relation given by Orr (1966).

Drop Composition

The drops are assumed to consist of water containing dissolved salt and suspended alumina. The complete reaction of HCl with the original hydroxide solution should produce about 4.52 kg mol/s of salt if KCl or NaCl is produced or 2.26 kg mol/s if $CaCl_2$ is produced for the large rocket. The amount of alumina collected is equal to the amount that is collected on the drops, primarily by inertial impaction. Calculations of the collection efficiency using the method presented previously showed that more than 99.9% of the mass of the exhaust alumina should be collected. For the large rocket about 3 kgmol/s alumina would flow out in the liquid. The total dissolved and suspended solids concentration would then be about 5.5% by mass (for stoichiometric amount of Na_2CO_3).

Gas Loading

The amount of entrained liquid in the gas is calculated using Table 19:

$$\frac{Q_L}{Q_G} = 3.04 \text{ kg water/m}^3 \text{ gas}$$

or, including the dissolved and suspended solids, the liquid loading is 3.22 kg liquid/m^3 gas.

Allowable Pressure Drop

The rocket provides a tremendous amount of power to the scrubbing process. The pressure drop for a conventional entrainment separator is accounted for in the governing equations by raising the mixing chamber downstream pressure by various amounts until the rocket no longer supplies enough suction to keep the entrance pressure below local atmospheric (91.01 k Pa). This pressure drop is available to an entrainment separator. Based on Figure 35 about 0.2 atm or 20 k Pa (3 lbf/in^2) is available which is a great deal more than adequate for any conceivable type of entrainment separator.

Required Efficiency of the Entrainment Separator

The required efficiency of the entrainment separator will depend on three factors. The first is the tolerable deposition of water, alumina, salts, and minute amounts of unreacted acid and hydroxide in the vicinity of the rocket scrubber. The second factor is economic, relating to the cost of the entrainment separator and to the cost saving from recycling the scrubber liquor. The final factor is possible future limits on fluoride salt emissions. Additionally, the entrainment separator will cause an increase in the gas residence time in the system to help ensure complete mixing and chemical reaction. The entrainment separator also is a flow impediment which reduces the force of "blowback" which occurs when the rocket motor burns out. Other than cost there are two negative factors. The separator causes enough of a pressure drop that pressure relief must be provided for at startup; and it must be carefully designed so that pockets of combustible hydrogen and carbon monoxide do not form.

Tolerable Deposition -

The deposition of alumina and salt would be tolerable if the usage were infrequent and the environmental impact on the surroundings neglibible. Proximity to metal surfaces which may be corroded by the salt and to agricultural land would make the deposition intolerable. The effects on plants are described by Lerman (1976).

Cost -

The cost of entrainment separators will be detailed later, but, as a general rule, they are relatively expensive. They are more than twice as costly as the scrubber shell itself, so their elimination from the system would greatly reduce costs. The costs saved by recycling the scrubber liquor depend on the local water costs and the frequency of scrubber use. A small, frequently used system could probably benefit from recycling the scrubber liquid. However, recycling would be limited to some extent by the buildup of chloride ion (Cl^-) which would reduce the solubility of HCl.

Future Limits on Fluoride Salts -

The U.S. Environmental Protection Agency has proposed emissions standards for total fluorides only for primary aluminum reduction plants and phosphate fertilizer plants (Chaput, 1976). Also, the latest National and California ambient air quality standards do not single out fluorides as a significant pollutant (California ARB Bulletin, March 1976). However, other countries do have air quality standards for fluorides according to Stern (1971) and the harmful effects of fluorides on vegetation (Brandt and Heck, 1968) and animals (Stokinger and Coffin, 1968) have been documented. Thus, it is possible that emission of fluoride salts contained in the scrubber liquid drops such as CaF_2 would have to be controlled to a certain limit.

Types of Separators

A number of types of entrainment separators could be used on the rocket scrubber since the allowable pressure drop is not a problem. The flow velocity for most separators such as mesh, packed bed, tube bank, and zig-zag baffles must be below 10 meters/second in order to keep reentrainment to a minimum. To reduce the flow velocity from about 100 m/s to 10 m/s would require an increase in area of 10 times. This increase would mean that the flow area of the entrainment separator would have to be about 500 m for the large rocket. The internals for such a cavernous structure would be expensive as compared to the empty volume of a cyclone separator. Additionally, mesh and packed bed separators are susceptible to plugging due to the solids present in the liquid drops. The alternative design would be a cyclone separator which can use the high energy available from the rocket to its advantage.

Cyclone Entrainment Separator Design

The cyclone causes the streamlines of the flow to curve so that a centrifugal force acts on the drops. The centrifugal force causes the drops to be deposited on the sides of the cyclone and eventually drain away as liquid effluent. In order to prevent reentrainment of liquid from the cyclone walls the gas inlet velocity must be kept below about 40 m/s. A typical cyclone is pictured in Figure 45.

The equations for the efficiency of cyclones are given by Calvert, et al. (1975).

The overall efficiency of the cyclone can be predicted by integrating the penetration equation over the drop size distribution. Calvert, et al. (1972) (Figure 8.2-4) have performed this integration for log-normal distributions.

The dimensions of the cyclone have to allow for vortex development and the inlet must be sized to keep the velocity below the 40 m/s. The following equations satisfy these criteria:

$$ab = Q_G/40$$
$$D_e = (Q_G/42)^{1/2}$$
$$h = 6\ D_e$$
$$D_c = 2\ D_e$$
$$b = 0.7\ D_e$$
$$a = 1.5\ D_e$$

where all dimensions are in meters. The dimensions of "a" and "b" may be a little greater than usually encountered, so that the calculated efficiency will be optimistic. The pressure drop through a cyclone has been found by Calvert, et al. (1975) to be:

$$\Delta P = 4.96 \times 10^{-6}\ \rho_G \left(\frac{Q_G}{a\ b}\right)^2 \left(2.8\ \frac{a\ b}{D_e^2}\right) \qquad (59)$$

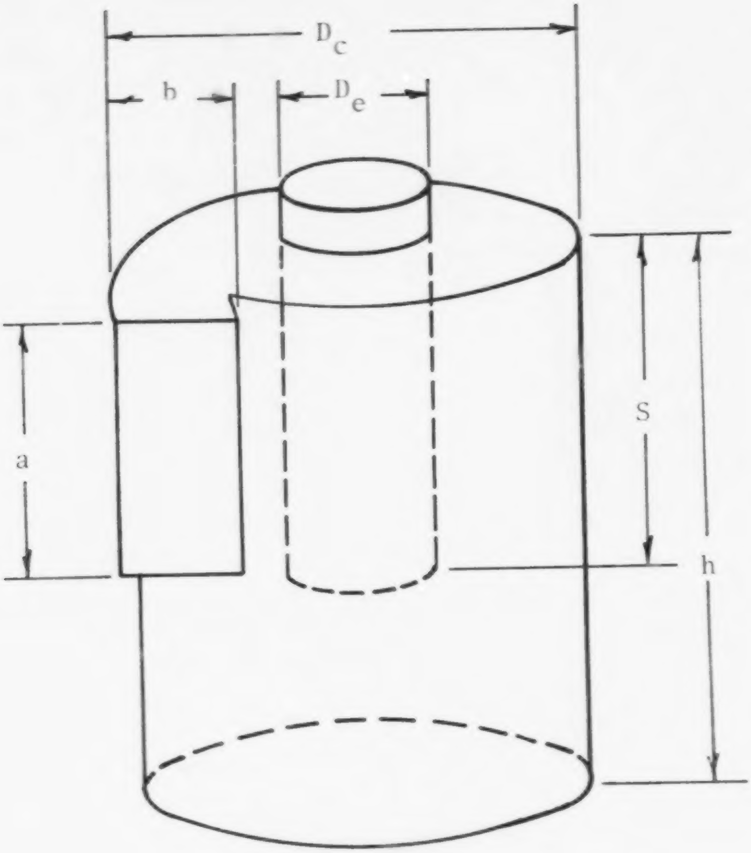


Figure 45. Cyclone with tangential gas inlet.

where ΔP = pressure drop, atm
ρ_G = gas density, kg/m^3
Q_G = volumetric flow rate, m^3/s (each cyclone)
a = cyclone inlet height, m
b = cyclone inlet width, m
D_e = cyclone exit diameter, m

Design for Large Rocket -

Thrust F = 2 MN
Q_G = 3,350 m^3/s

It is obvious that a number of cyclones are required to keep the diameter within reason. Chose,

$$D_c = 8 \text{ m}$$

then,

$$h = 24\text{m}$$
$$D_e = 4 \text{ m}$$
$$a = 6 \text{ m}$$
$$b = 2.8 \text{ m}$$
$$Q_G = 40 \text{ ab} = 672 \text{ m}^3$$

so, 5 cyclones are required.

The pressure drop is,

$$\Delta P = 0.013 \text{ atm}$$

The efficiency is about 99.4%, which may be a slight overestimate. However, a specific required efficiency has not been set so that this may or may not meet future requirements. Higher efficiencies could be achieved by increasing the cyclone volume.

Relief Ports

Provision for pressure relief hatches at the top of the cyclone separator is required. These relief ports should allow the air present in the system at rocket start-up to exhaust. The instantaneous character of the rocket ignition will cause a compression wave to be generated which could rupture the scrubber duct or cyclone if not relieved. A typical design would be a heavy hinged gate which would open when a certain pressure is reached and close by gravity when the operating pressure is obtained. More costly spring-held relief ports are also feasible. The gas emitted through these relief ports would not affect the emission of pollutants since it consists primarily of air.

CONVENTIONAL SCRUBBER COSTS

Introduction

In a previous subsection preliminary cost estimates were made to determine the least expensive type of scrubber for rocket exhaust cleaning. Here the costs are detailed for the selected gas-atomized scrubber and applied to rockets of any thrust between 20 kilonewtons (4,500 lbf) and 2 meganewtons (450,000 lbf).

The procedure adopted in preparing the total project costs follows Guthrie (1970). In essence the total project costs are prepared by summing individual bare module costs. Modules in our case are of three types, two direct and one indirect.

Modules

The direct cost modules may be classified as the chemical processing module and the offsite facilities module. In general, the former covers all those items which would normally appear in a typical chemical process flow sheet such as pumps, vessels, exchangers, etc., while the latter encompasses those items situated external to the process battery limits such as sewerage, waste treatment, water distribution, etc. The direct costs cover the costs for equipment, material and labor associated with the complete installation in the field. The total bare module cost for a particular item is o[illegible]d by adding to the direct module cost an indirect module cost. The latter comprises all costs associated with engineering, office overheads, freight, taxes, etc. and is estimated by applying a percentage figure to the direct costs.

Figure 46 summarizes the general format for a typical chemical process module. It will be noted that the individual cost items making up the total material and labor costs are based on applying percentage figures to the basic equipment FOB cost. For example, the costs for piping required to tie in a piece of equipment to the process is 32.0% of the FOB cost. The total material cost (FOB equipment and installation material) is obtained by multiplying the FOB equipment cost by a material factor

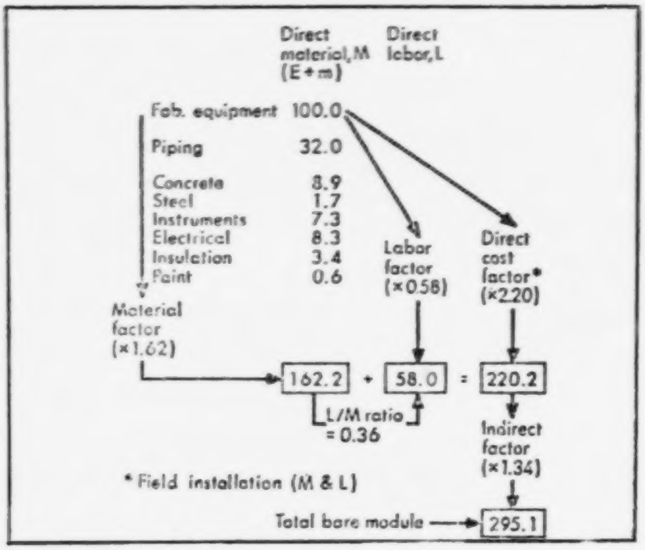

Direct material, M (E+m)
Direct labor, L
Fab. equipment 100.0
Piping 32.0
Concrete 8.9
Steel 1.7
Instruments 7.3
Electrical 8.3
Insulation 3.4
Paint 0.6
Material factor (×1.62)
Labor factor (×0.58)
Direct cost factor* (×2.20)
162.2 + 58.0 = 220.2
L/M ratio = 0.36
Indirect factor (×1.34)
*Field installation (M & L)
Total bare module 295.1

Figure 46 . Outline of module cost format (factors presented are examples only).

of 1.62. Similarly, labor costs for equipment installation is 0.58 times the FOB costs. Total direct costs are obtained by summing the direct material and direct labor cost factors and applying this to the FOB cost to obtain the total indirect module cost.

As mentioned earlier, the indirect module is obtained as a percentage of the direct module cost. This is indicated in the figure at 34% (indirect factor = 1.34). Summing the direct and indirect module costs gives the total bare module costs.

It should be noted that the numbers presented for the cost factors are examples only. These vary from module to module depending on the type of unit process being costed.

Total costs associated with the offsite facilities are obtained in essentially the same manner as those for the chemical process. The main difference is the absence of a process equipment FOB cost. In this instance the total direct costs are obtained by itemizing and summing labor and material costs to obtain the direct module cost. From this step on the procedure is identical to the chemical process module.

The grand total for the project was obtained by adding percentage figures to the summed module costs to account for contingency and fee. Examples of the complete costing procedure are presented in a latter part of this section.

Equipment Costs

A knowledge of the equipment FOB cost is fundamental to the module approach to cost estimating. In the case of field erected items, the total direct labor and material costs are needed. These were taken in most part from the literature. In some instances vendor quotes were solicited to either confirm the published data or to obtain updated figures.

The 2.0 meganewton rocket size was chosen as the basis from which to scale all other rocket sizes. Scaling was performed in most cases by using literature cost exponents. The exceptions are noted in the text which follows.

Figures 47 through 56 present the costs for the individual process components listed in Table 20. The data have been presented on a cost versus rocket thrust format to simplify the total cost estimating job. Note that the figures are for total installed costs. These include all equipment costs, direct material and labor costs required for field installation and project indirects. Each of these separate items may be obtained by applying the cost factors noted on the graphs. The total project costs may be estimated by summing the module costs and adding figures for the contingency and fee. A figure of 18% has been recommended by Guthrie (1970) for this purpose.

The following summarizes the derivation of the data presented in Figures 47 through 56.

A) Quench duct, atomized spray scrubber and cyclone cost, Figures 47 through 49.

Costs for the quench duct, the atomized spray scrubber and cyclone costs were based on assuming field assembly of shop prefabricated units. Shop costs were based on material weight and fabrication manpower as presented by Calvert et al. (1972).

TABLE 20. LIST OF PROCESSING UNITS MAKING UP THE TOTAL CONVENTIONAL SCRUBBING PROCESS

Quench duct

Spray scrubber

Cyclones (separator)

Water storage tank

Caustic pumps

Caustic tank

Pipeline (water supply)

Liquor supply pump

Drainage sewer

Drying bed (waste treatment)

Cost exponent, labor and material factors were taken from Guthries "norm" for chemical process modules. Indirects were taken at 60% of the directs as opposed to the 34% "norm". This was to allow for the non-conventional nature of these processing items which would required higher investment.

B) Water storage tank costs, Figure 50.

Water storage tank costs have been presented for the purpose of making cost estimates for a complete grass roots project. The current set-up at the test base could use the existing water storage tank located at the top of Haystack Butte and this would eliminate this cost for the existing set-up.

The costs presented in Figure 50 were based on Guthrie (1970) and assume field erection throughout.

C) Caustic supply pump, Figure 51.

The maximum pump size considered for the current application was taken at 2,000 gal/min. Scrubbing units requiring flows greater than this were assumed to use multiple pump units to meet the required capacity. The figures presented in Figure 51 were based on the data in Guthrie (1970) for centrifugal, motor-driven pumps.

D) Caustic storage tank costs, Figure 52.

Caustic storage tank costs assume field erection of shop fabricated vessels. The numbers are based on Guthrie (1970) for API conical vessels.

E) Pipeline Costs, Figure 53.

The pipeline costs presented in Figure 53 assume the quench and scrubber liquor water would be gravity fed from storage tanks situated on top of Haystack Butte. For large rockets this is the least expensive route. However, as the rocket size is lowered a trade-off point is reached where the cost of piping from the hill to the scrubber (182 m) equals the cost of pumping from a locally situated storage tank. This point was taken at 0.1 MN (22,500 lbf) in this work and was arrived at from consideration of pipings, pumps and power costs. A similar tradeoff would be needed for other test sites.

Current material costs were obtained from vendor quotes. Field installation labor hours were taken from Guthrie (1970) and charged at the average crew labor rate of $10 per hour. A figure of 20.0 percent was added to the sum of these costs to allow for valves and other piping auxiliaries such as flanges, bends, etc. These costs were escalated 50% to allow for the unusual field conditions found at the test area. Indirect costs were based on Guthrie (1970) and taken at 30%.

F) Scrubbing liquor supply pumps, Figure 54.

As mentioned earlier, for rockets smaller than 0.1 MN it may be more economical to pump the scrubbing liquor from a locally situated storage tank. Costs for these pumps are presented in Figure 54. The maximum pump size was chosen at 2,000 gal/min. All costs and cost factors were based on Guthrie (1970) for motor driven centrifugal pumps.

G) Drainage sewer costs and drying bed costs, Figures 55 and 56.

Drainage sewer costs and drying bed costs were based on information taken from Lee Saylor (1976). Sewer costs presented in Figure 55 were prepared from estimates made for a number of rocket sizes. The figures include all costs associated with sewer construction and include pipe costs, excavation, shoring, backfill, etc. Drying bed costs shown in Figure 56 include construction costs for excavation, grading, compacting, etc. Linear costs were obtained from vendor quotes. A figure of 40% was added for indirects per Guthrie (1970).

Total Installed Costs

Figure 57 shows a summation of all the cost modules for total cost versus rocket thrust relationship. Two lines are shown to differentiate between gravity feed through a 182 m pipeline from the hilltop or pumping from a local tank. The breakpoint of 0.1 MN thrust is somewhat subjective and based on the point at which operating (power) costs become significant. The contingency and fee factor of 18% is included in the figure.

Scrubber Costs - Worked Examples

Two worked examples of cost estimates made for conventional gas atomized scrubbers are presented in Table 21. These are for three levels of rocket thrusts. It can readily be appreciated that the costing procedure is straight forward and needs little by way of explanation. In essence, total costs are estimated by summing the installed costs for the components listed in the Table with the individual item costs taken from Figures 47 through 56. To the sum is added a percentage to allow for contingency and fee.

It is worth reiterating that at Haystack Butte rockets smaller than 0.1 meganewtons show no pipeline costs since scrubbing liquor is supplied via pumps from locally situated storage tanks. Conversely, rockets greater than this size show pipeline costs. These units are assumed gravity fed from storage tanks in a situation similar to that existing at Haystack Butte. Total project installed costs for 2.0 meganewton (450,000 lbf), 0.22 megamewton (50,000 lbf), and 0.022 meganewton (5,000 lbf) rockets are \$4.26 million, \$1.16 million, and \$208,000 respectively, based on December, 1976 dollars.

TABLE 21. WORKED EXAMPLES OF CONVENTIONAL GAS ATOMIZED SPRAY SCRUBBER

Rocket thrust, meganewtons	2.0	0.22	0.022
Rocket thrust, pounds-force	450,000	50,000	5,000
Cost Item		Cost $1,000	
Quencher	210	54	13
Spray Scrubber	280	74	23
Cyclones	1,400	370	92
Water Tank	112	28	7
Caustic Pump	140	13	2
Cuastic Tank	23	11	5
Pipeline (water supply)	1,220	400	--
Liquor Supply Pump	--	--	23
Drainage Sewer	155	27	10
Drying Bed	72	8	1
Installed Cost	$3,612	$985	$176
Contingency + Fee @ 18%	650	177	32
Total Installed Cost	$4,262	$1,162	$208

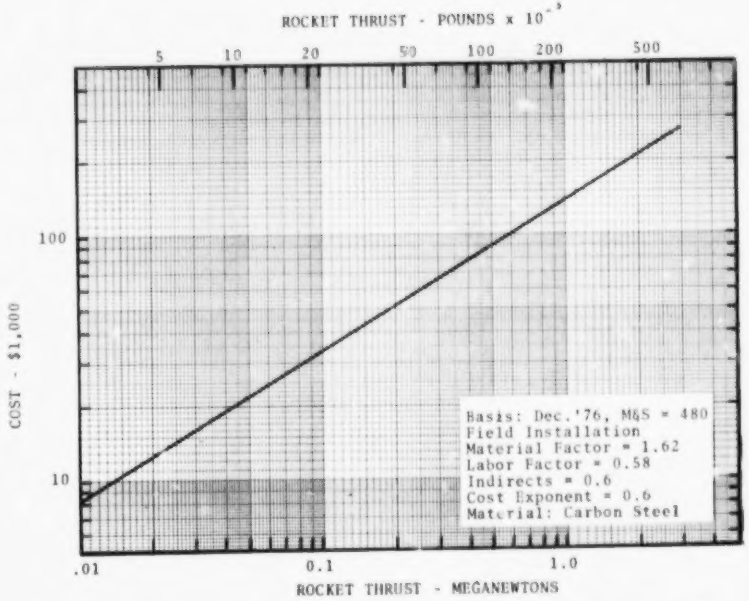


Figure 47. Quench duct installed costs (figures include shop and field materials, labor and indirects).

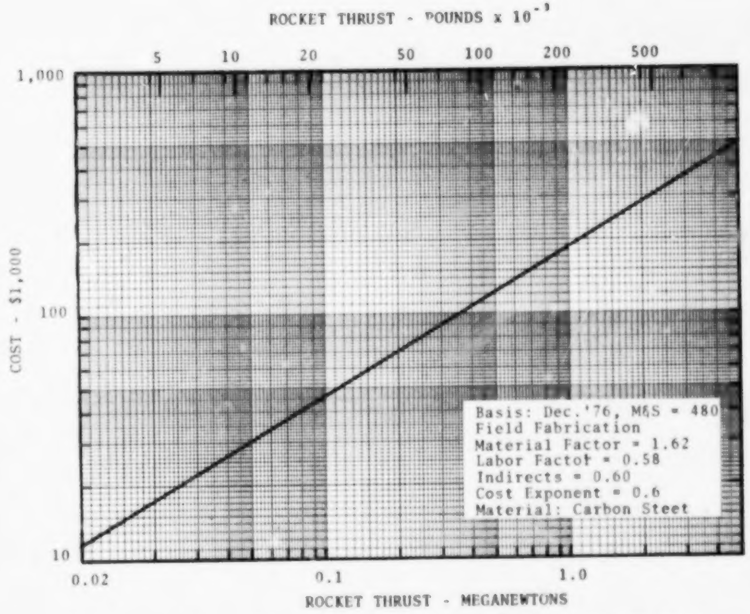


Figure 48. Atomized spray scrubber costs (figures include field materials, labor and indirects).

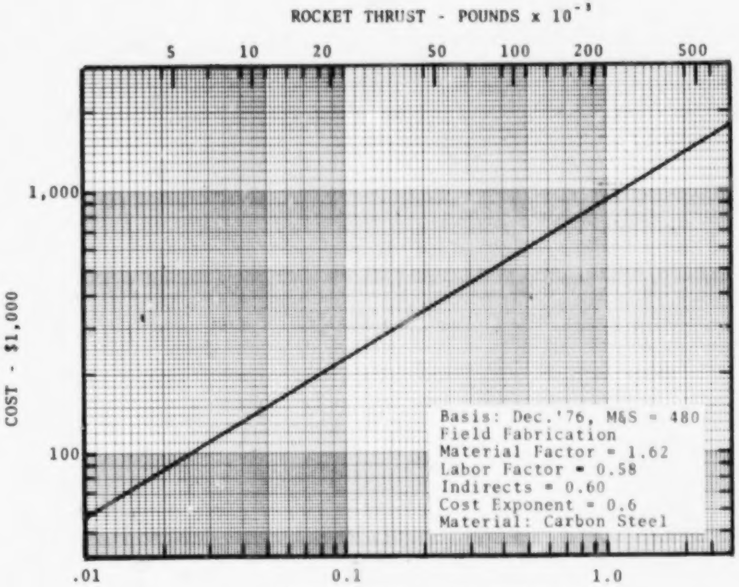


Figure 49. Cyclone costs (figures include field materials, labor and indirects).

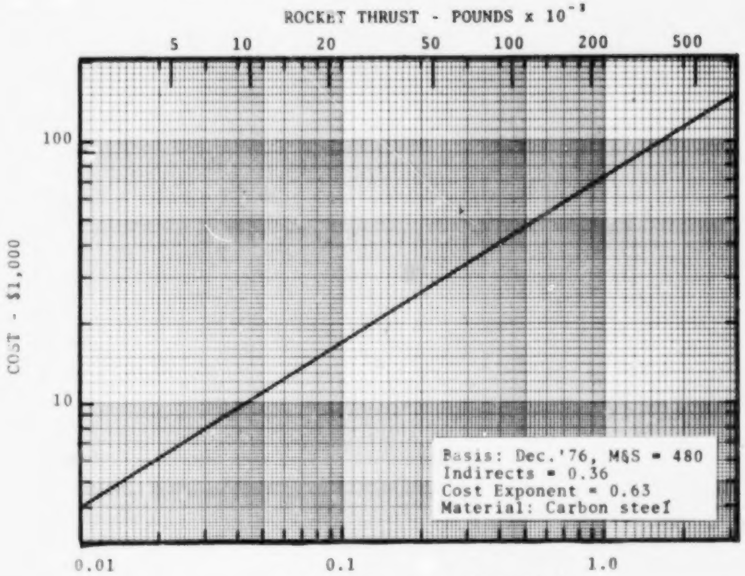


Figure 50. Water storage tank costs.

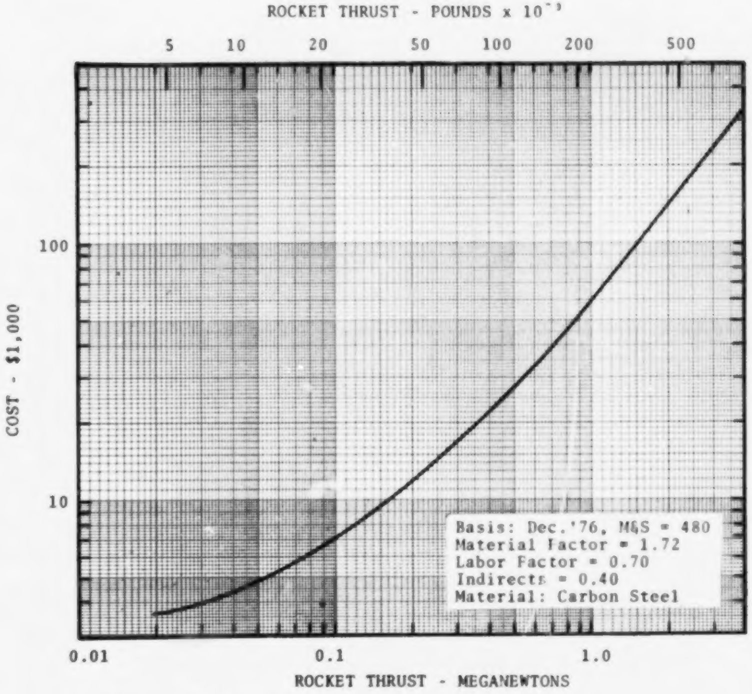


Figure 51. Caustic slurry supply pump costs.

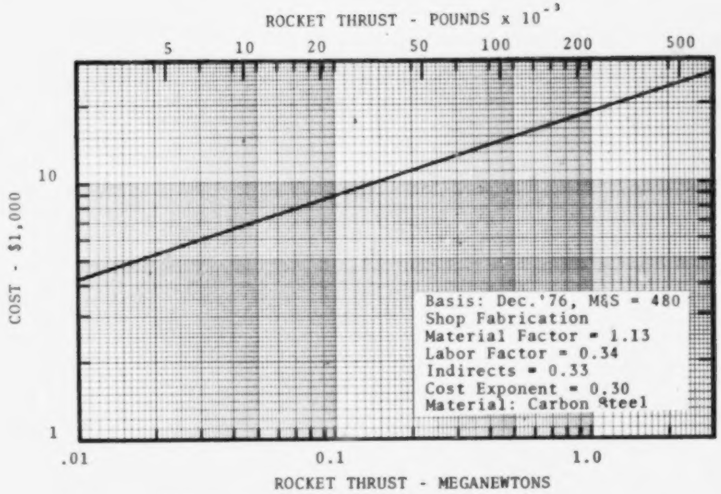


Figure 52. Caustic storage tank costs.
- API conical
(Figures include shop and field materials, labor and indirects).

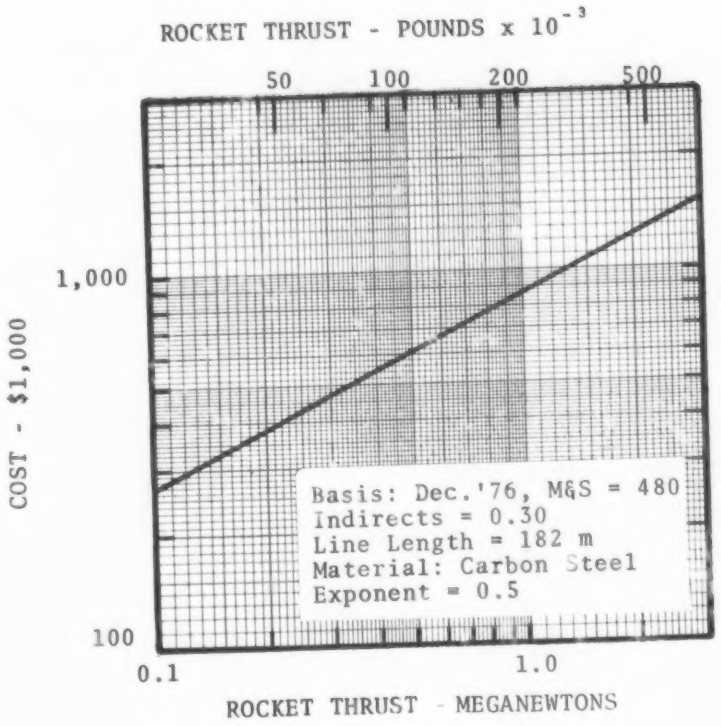


Figure 53. Pipeline costs.

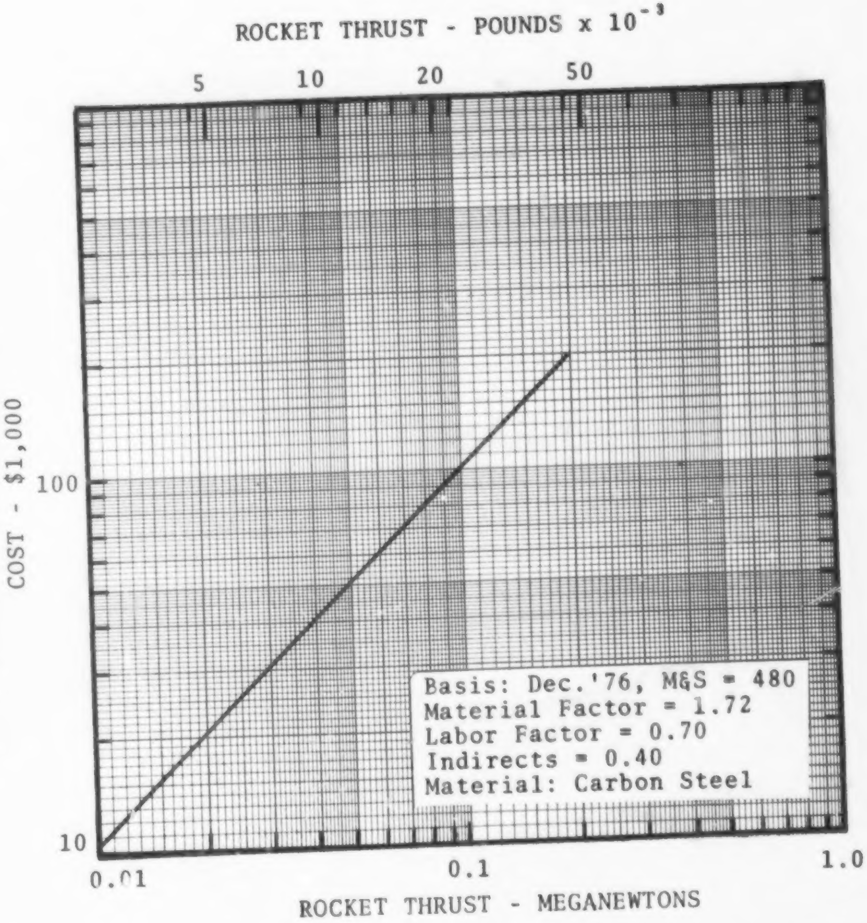


Figure 54. Quench and scrubbing liquor pump costs for small rocket scrubbers.

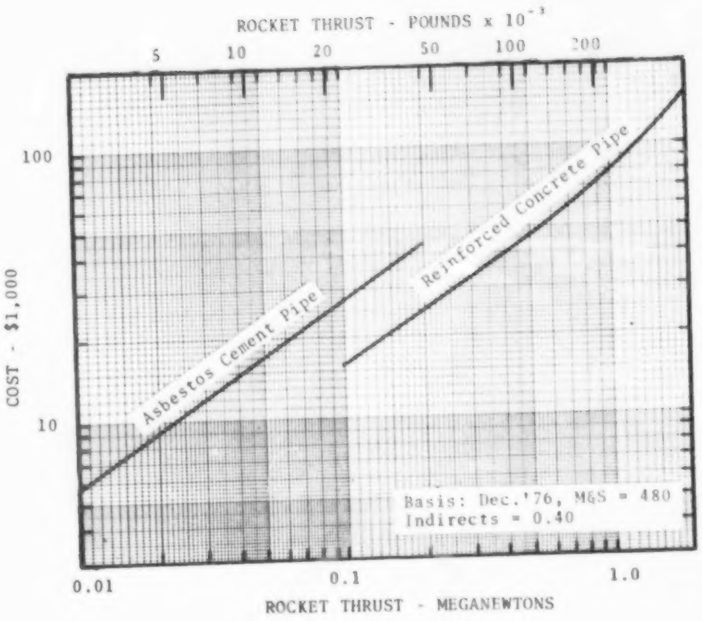


Figure 55. Drainage sewer costs.

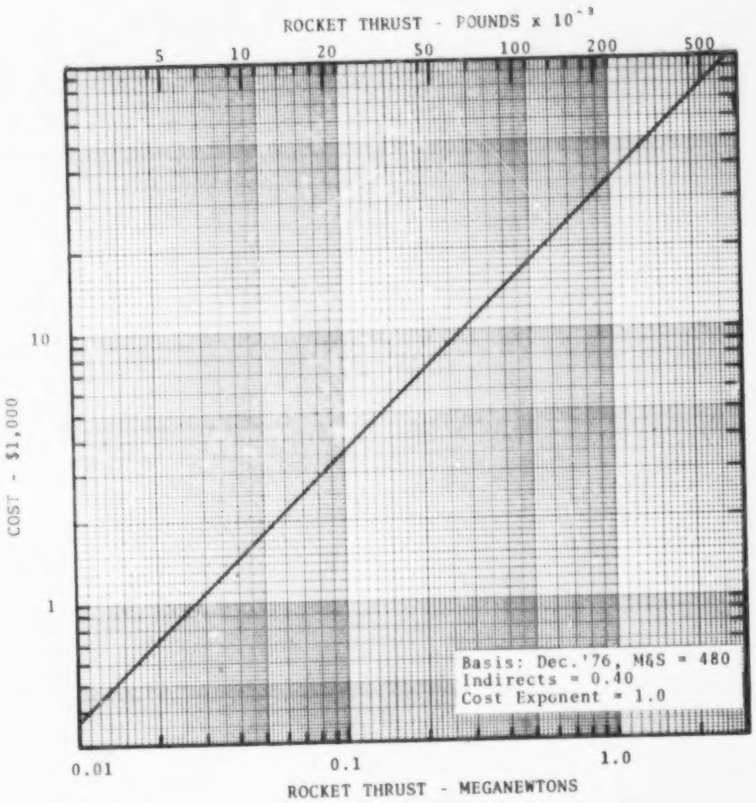


Figure 56. Drying bed costs (figures include total materials, installation and indirect costs).

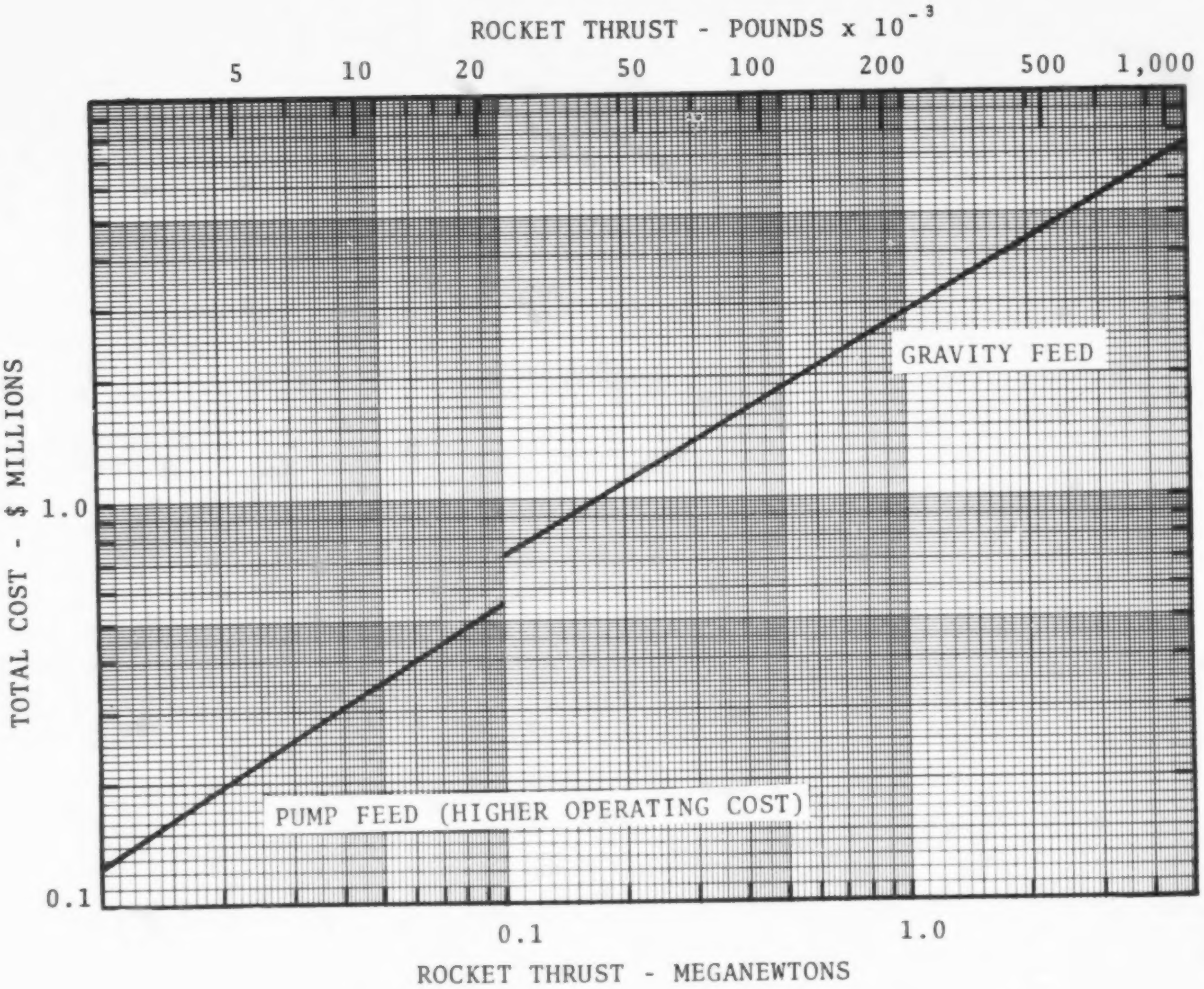


Figure 57. Total installed costs for conventional scrubbers (December 1976).

UNCONVENTIONAL SCRUBBER DESIGN

Introduction

Although any scrubber designed for rocket exhaust cleanup is unusual, the design previously called "conventional" is a widely used gas-atomized spray scrubber. Because of the high cost of such a system for infrequent use, an alternative design is proposed. The major criterion for this alternative, or unconventional, design is to achieve the least possible cost for a system that could reasonably be expected to adequately scrub the rocket exhaust. The major emphasis is placed on a design for the largest rocket, where the largest cost savings could be realized.

Ideas Considered

Several ideas were investigated and rejected on either feasibility or economic grounds. One idea was to air-drop a neutralizing solution on the ground cloud. The National Aeronautics and Space Administration (NASA) was considering this idea for launches of the Space Shuttle. For the AFRPL application it seemed that there were too many problems with this idea. Major among these problems was the probable scrubbing efficiency. A slight miscalculation of the trajectory could result in a partial miss of the exhaust cloud. Missing the cloud could result in rain-out of caustic on the surroundings as well as a poor scrubbing efficiency. It was also felt that since NASA was already pursuing this idea that another line should be followed in this study.

Another idea was to construct a network of spray manifolds, extending out into the desert, that would encompass the rocket exhaust plume. As envisioned this concept would use high pressure spray nozzles to distribute the neutralizing liquid throughout the plume, with no walls required. This idea was not that inexpensive because of the length of pressurized piping needed. Also, it was susceptible to inefficiency, whenever the wind would blow the plume out of the spray network.

Selected Design

A.P.T. has conceived an unconventional design which takes advantage of the topography of Haystack Butte at AFRPL to create an open spray scrubber. The scrubbing liquid is gravity fed through open culverts to the open scrubber channel to avoid the high cost of the piping. A wall is used on the downhill side to reduce wind effects and contain the exhaust plume and spray. Figure 58 presents a schematic of the concept while a plan view sketch of the proposed system is given in Figure 59.

The rocket exhaust is first led through the deflector to the transition piece which consists of a simple section of ductwork constructed from materials capable of withstanding the high temperatures of the rocket gas. The purpose of the transition piece is to take the gas from the deflector to the beginning of the quenching and scrubbing excavation. The cross-sectional area of the transition piece was taken at 9.0 square meters and covers a distance of about 35 meters.

Cooling of the hot gas and mass transfer of the contaminants to the spray liquor takes place in the cooling and scrubbing section. It is envisioned this would be constructed by excavating the hillside. One side and the bottom of the scrubber cross section are stabilized with gunite. The remaining side is made from corrugated sheet steel suitably supported while the top remains open. Figure 60 presents a view of a typical cross section illustrating these principles. The cross-sectional area of the excavation expands from an inlet of 25 square meters to an outlet of 600 square meters over a length of approximately 50 meters. The exit dimensions were chosen to provide a gas velocity of 5 m/s for entry to the entrainment separator.

To facilitate slowing down the gas, horizontal and vertical baffles are attached to the base and side of the excavation, the aim being to remove momentum through drag. These are illustrated in the sketch of Figure 60.

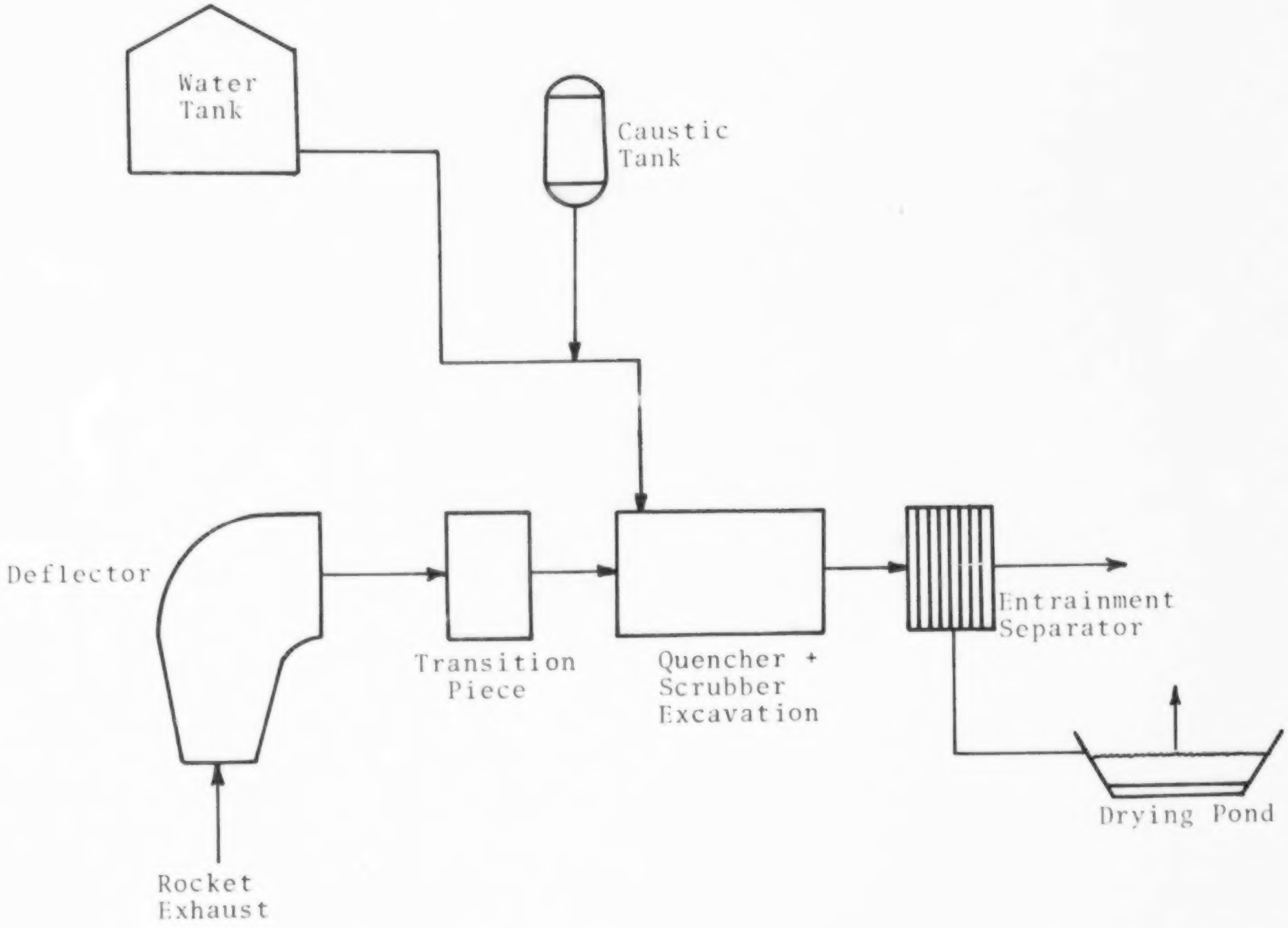

Water Tank
Caustic Tank
Deflector
Transition Piece
Quencher + Scrubber Excavation
Entrainment Separator
Drying Pond
Rocket Exhaust

Figure 58. Schematic of non-conventional rocket exhaust gas scrubbing process.

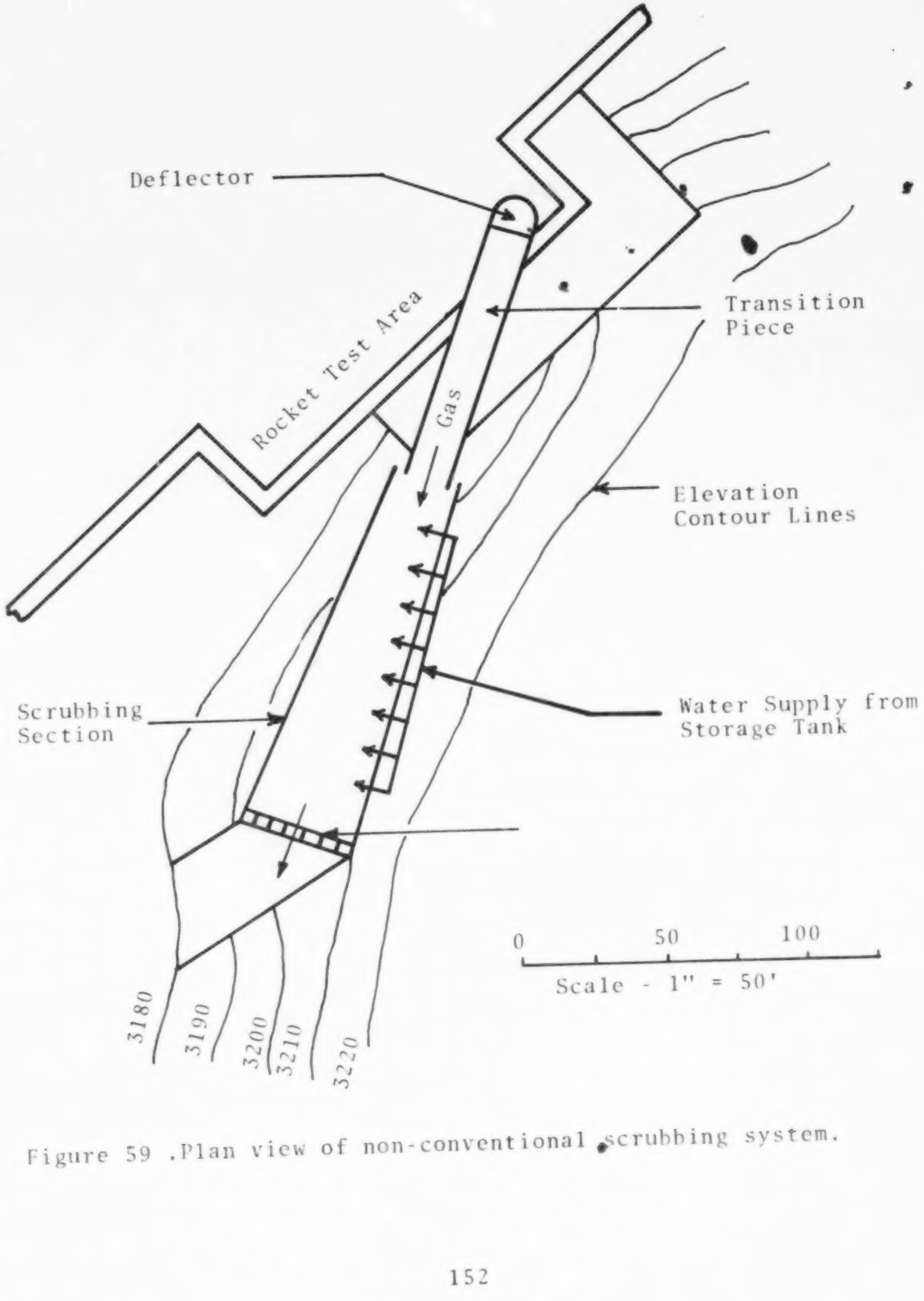

Deflector
Transition Piece
Rocket Test Area
Gas
Elevation Contour Lines
Water Supply from Storage Tank
Scrubbing Section
0
50
100
Scale - 1" = 50'
3180
3190
3200
3210
3220

Figure 59 .Plan view of non-conventional scrubbing system.

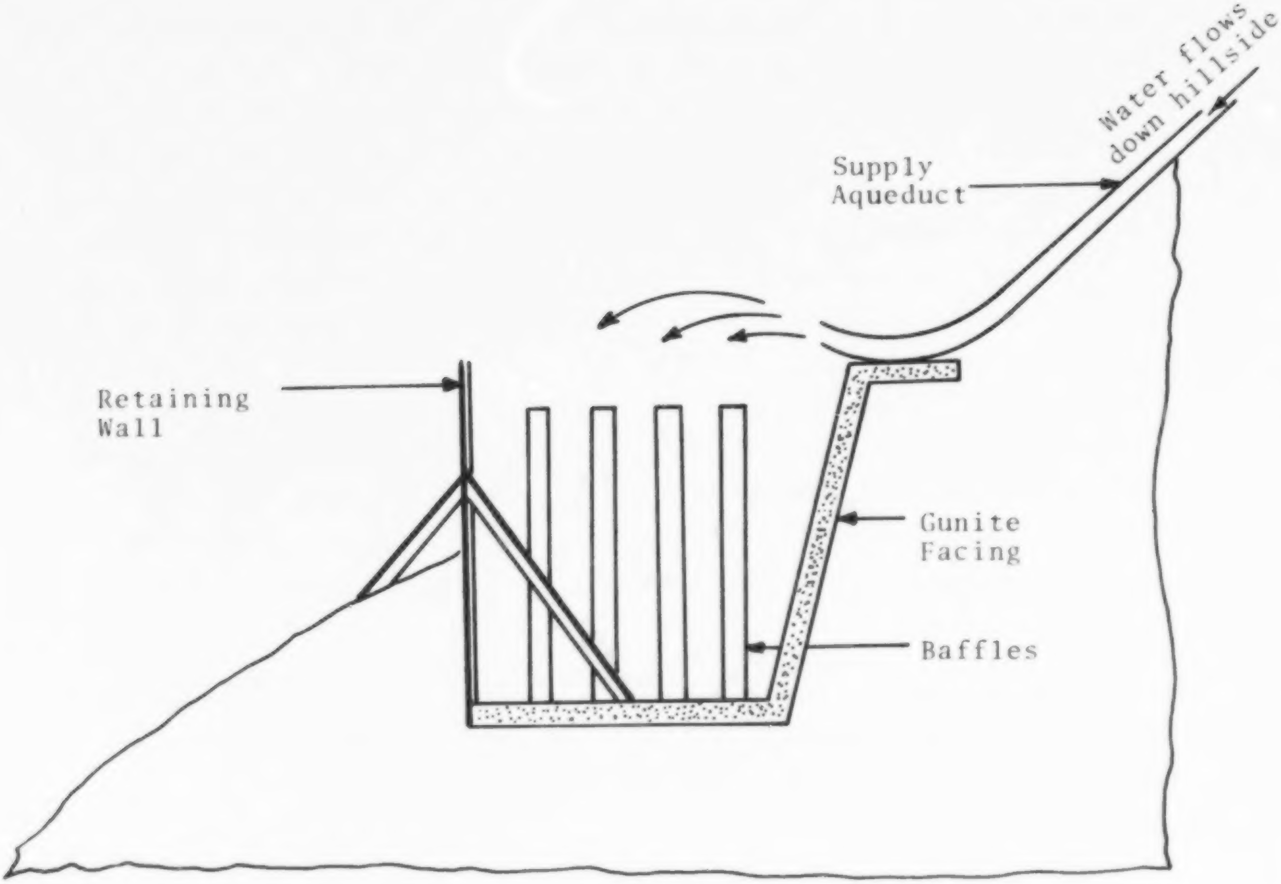

Water flows down hillside
Supply Aqueduct
Retaining Wall
Gunite Facing
Baffles

Figure 60. Typical cross-section of a non-conventional absorber configuration.

Water required for cooling and scrubbing is gravity fed via an open culvert from the water storage tank on Haystack Butte. Base required for neutralization is also gravity fed at a point close to the start of the water run. The scrubber liquid is then discharged into an open spray manifold designed to distribute the liquor along the length of the excavation. As the liquor traverses the gas plume, momentum will be lost to the liquor thus helping to slow down the gas. Simultaneously, the liquor will be atomized providing the surface area required for mass transfer from the gas to the liquid and the drop for collecting particles. Some of the liquid drops fall from the plume over the trajectory length while the remainder are removed in the entrainment separator located at the end of the scrubber excavation.

The entrainment separator is built across the exit of the excavation and is envisioned as being a tube bank type. The scrubbing liquor removed in the separator combines with the liquor fallout from the gas plume and flows under gravity in an open conduit to the waste treatment drying bed.

Process Design

Since the source process is the same for the unconventional as well as the conventional and both use a spray design, the process parameters are similar.

Equilibrium Conditions -

As with the conventional design the quencher and scrubber can be considered one unit. However, the equilibrium cross section is a function of the scrubbing liquid rate since the scrubber is open to the atmosphere. In the subsection on quenching the area, gas density, temperature, and velocity were determined as functions of the liquid to rocket mass flow rate ratio for the quencher. These curves apply to the scrubber as well.

The equilibrium mass transfer is practically the same as for the ducted spray scrubber. The previous analysis showed that the total system (quencher and scrubber) liquid flow rate should be 15 kg water per kg propellant for adequate mass transfer. Based on Figure 38 this corresponds to the following conditions:

TABLE 22. EQUILIBRIUM CONDITIONS IN UNCONVENTIONAL SCRUBBER WITHOUT BAFFLES

R_w = 15 kg water/kg propellant

R_a = 0.1 kg air/kg propellant

$A = 20\ m^2$

$\rho_G = 0.54\ kg/m^3$

T = 92°C

u = 160 m/s

$Q = uA = 3{,}200\ m^3/s$

The velocity, u = 160 m/s is too high. A lower velocity is required so that large drops will settle out in the scrubber and a low pressure drop entrainment separator can be used. This lower velocity can be accomplished by using baffles to expand the plume to a larger cross section (A). The baffles will also create drag which will reduce the velocity. For the large amount of water input the effect of velocity on the equilibrium temperature will be slight so that the volume flow rate will not be affected by the baffles. The baffles will also serve to knock out the scrubber liquid drops and create more turbulent mixing.

The mass transfer length has been shown to be on the order of a few meters for the spray scrubber, which is much less than the designed 50 meter quencher/scrubber length.

Coupling Effects Between Scrubber and Rocket

At Haystack Butte the rocket could be affected by the thrust deflector in the same manner as the quencher inlet of the conventional scrubber described previously. The unconventional scrubber section itself is located where it will not have any effect on the rocket.

Thrust Deflector

Because of the vertical configuration of the test rocket at Haystack Butte a deflector is required to direct the exhaust into the scrubber. Design and cost information should be available from the companies who constructed the thrust deflectors used for the National Aeronautics and Space Administration very high thrust rocket tests at AFRPL. Those NASA thrust deflectors were capable of deflecting a downward thrust of 6.7 meganewtons (1.5×10^6 lbf) to the horizontal.

UNCONVENTIONAL SCRUBBER ENTRAINMENT SEPARATION

Introduction

The primary function of the rocket exhaust scrubber is to remove the halogen acid gases produced. If a basic scrubbing solution is used and the reaction with the halogen acid within the scrubbing drops produces a non-toxic salt then there is no need to remove the drops. In the case of rocket exhausts containing hydrogen fluoride the production of a truly non-toxic salt in the scrubbing drops may be practically impossible. However, as of October, 1976, there is no specific rule in California concerning the emission of fluoride salts.

Another argument against the need for an entrainment separator on the open, unconventional scrubber design is based on the rapid slowdown of the gas after leaving the scrubber. The gas is not confined to a duct, but is completely free to expand and diffuse, and will lose its velocity in a short distance. The drops which have more momentum will carry a little farther but they will also quickly slow down. Although the detailed calculation for this two-phase wake flow have not been made, the argument appears to be valid.

There are at least two reasons why an entrainment separator might be required. First, the local air pollution control district may tighten the restrictions. Specific rules on fluoride salts, for example, may be forthcoming. Secondly, other reasons may exist which would require the entrainment to be removed immediately following the scrubber. Proximity to other structures or sensitive areas where salt spray would cause problems are reasons for having an entrainment separator.

Entrainment Separation Within Scrubber Section

The unconventional scrubber is designed to have the scrubbing liquid carried into it at several locations along its 50 meter length. As the gas traverses the trajectory path it will lose momentum to the scrubbing liquor resulting in the atomization of droplets of increasing size. The larger droplets atomized at the low gas velocities will collect the smaller droplets formed at the high velocities through inertial impaction. This results in an overall larger mean droplet size for final separation. A study of the collection of small droplets via impaction and definition of a final droplet size for ultimate separation was performed.

Drop Size From Critical Weber Number -

According to Calvert (1968), the stable droplet size for water drops in gas streams may be predicted from:

$$We = \rho_G (u_G - u_d)^2 \frac{d_d}{2\sigma} \approx 5 \qquad (60)$$

where We = Weber number, dimensionless

ρ_g = gas density, g/cm³

u_d = drop velocity, dm/s

u_G = gas velocity, cm/s

σ = surface tension, dynes/cm

d_d = drop diameter, cm

Hidy (1970) suggests a critical Weber number = 6.5.

The maximum stable drop diameter will be predicted when the term $(u_G - u_d)$ tends to zero. However, for the present case the maximum will be predicted when either "u_G" or "u_d" is zero. For this condition "u_d" equals the terminal settling velocity, u_{ts}, and for drops greater than 0.15 cm in diameter this may be expressed:

$$u_{ts} = 1.74 \left(\frac{g \; d_d \; \rho_d}{\rho_G} \right)^{0.5}, \text{ cm/s} \qquad (61)$$

where g = gravitational constant

ρ_d = drop density, g/cm³

Equating (60) and (61) shows that a stable drop diameter of about 0.5 cm will be formed at gas velocities less than 16.0 m/s. This drop size corresponds to the terminal settling velocity of the drop and will not change regardless of gas velocities below this figure. Put in other words, slowing the gas below 16.0 m/s will not affect drop size.

Drop Size from Nukiyama-Tanasawa Relation-

The Nukiyama and Tanasawa equation discussed previously may be used to predict atomized drop size at the high velocities:

$$d_{ds} = \frac{50}{u_G} + 91.8 \left(\frac{Q_L}{Q_G}\right)^{1.5} \tag{62}$$

where d_{ds} = the Sauter mean diameter, cm
u_G = gas velocity, cm/s
and (Q_L/Q_G) is dimensionless

The Sauter mean diameter, d_{ds}, is related to the geometric mean diameter as follows:

$$\ln d_{ds} = \ln d_d - 0.5 \ln^2 \sigma_g \tag{63}$$

where σ_g = geometric standard deviation

The standard deviation for gas atomized drops is generally on the order of 2.0. With this information, drop diameter at the start of the scrubbing section, where "u_G" = 500 m/s, was computed to be at least 10 µm.

Collection of Small Drops on Large Drops -

The worst condition for design will be to capture those 10 µm drops atomized at the start of the scrubbing section. The most pessimistic viewpoint would be to consider no drop growth through impaction as the gas traverses the trajectory.

Drop collection would take place therefore only in the last stage of the scrubbing section on the large drops (0.525 cm) formed at the low gas velocities.

The mechanism for drop collection by impaction is described in Calvert, et al. (1972) and Yung, et al. (1976). The collection efficiency is primarily a function of collected drop size, liquid to gas ratio, collector drop size, and relative velocity between collected and collector drops. Assuming a relative velocity of 10 m/s, a collected drop diameter of 10 m and a collector drop diameter of 0.525 cm the fractional efficiency of collection is:

$$E \approx 1 - \exp\left(-1.2\ Q_L\right) \tag{64}$$

where "Q_L" refers to the volume flow rate (m^3/s) of the collector drops. The total liquid input to the scrubber section is about 11 times the mass flow rate of the rocket propellant ($R_w = 11$). The collection efficiency would be 60% if the R_w ratio of the collector drops were 1 and greater than 99% if the R_w ratio were 5. Since this is a worst case analysis in that the collected drops would actually be larger than 10 μm and the collector drops would actually be smaller than 0.525 cm, the conclusion is that a high percentage of the mass of the entrainment will be around 0.525 cm diameter.

Separation by Gravity Settling

Entrainment separation may be accomplished by gravity settling because the drop size predicted by the critical Weber number concept is sufficiently large.

The removal efficiency of drops falling under gravity in turbulent flow may be expressed by the equation of Calvert, et al (1975):

$$E = 1 - \exp\left(\frac{-u_{ts}\ L}{H\ u_G}\right) \tag{65}$$

where u_{ts} = the terminal settling velocity of the drop, m/s
L = horizontal distance travelled by the drop, m
u_g = gas velocity, m/s
H = total height fallen drop

For a gas plume of square cross section and uniform velocity the flow rate is,

$$Q_G = u_G H^2 \text{ , m}^3\text{/s} \qquad (66)$$

Substituting in equation (65) gives:

$$E = 1 - \exp\left(\frac{-u_{ts} L}{\sqrt{Q_G u_G}}\right)$$

According to Fuchs (1964), the terminal settling velocity of 0.525 cm diameter water drops is u_{ts} = 9 m/s. For Q = 3,200 m³/s and u_G = 5 m/s the removal efficiency of these drops would be 99% for a length of L = 65m. Actually, because of the flow resistance of the air this length would be shorter. Smaller drops would, of course, require a longer settling length. Because settling areas with lengths on the order of 65 m or longer may not be available at the site of the scrubber, separation by other means should be investigated.

Unconventional Entrainment Separator Design -

There are three inexpensive, low pressure drop designs that are applicable to the unconventional scrubber mist. One is a gravity settler which uses a parallel array of horizontal plates so that the parameter, H, in equation (66) is reduced. Another type uses a series of horizontal baffles and a third uses a bank of vertical tubes. The costs of these designs are comparable, so the choice must be based on other grounds. According to design equations given by Calvert, et al. (1975) the tube bank should be slightly more efficient than the other two and they present some data showing a slightly higher reentrainment velocity for the tube bank design.

Tube Bank Entrainment Separator - Figure 61 shows in schematic form the arrangement within a tube bank separator. In principle, liquid drops are separated from the gas stream by impaction on the tubes. The liquor is then removed from the process by gravity flow along the tubes to a suitable collection manifold. Calvert et al. (1975) present a mathematical model for tube bank design. Their models were used to determine the collection efficiency of a tube bank consisting 0f 3.34 cm (1.3 in) tubes at 2.54 cm spacing. The models show a single stage sufficient for almost 100% collection. Again this is due to the large drop size being collected. For practical purposes, a 3-stage unit would be the minimum for consideration and this has been used in the cost estimates.

Calvert et al. (1975) have also studied reentrainment in tube banks at the pilot plant scale. Their findings show no reentrainment for velocities below about 7 m/s. Since our design velocity is 5 m/s no reentrainment is expected.

The pressure drop in tube banks at 5 m/s is quite small. Calvert et al. (1975) found it to be on the order of 100 Pa (1 cm W.C.).

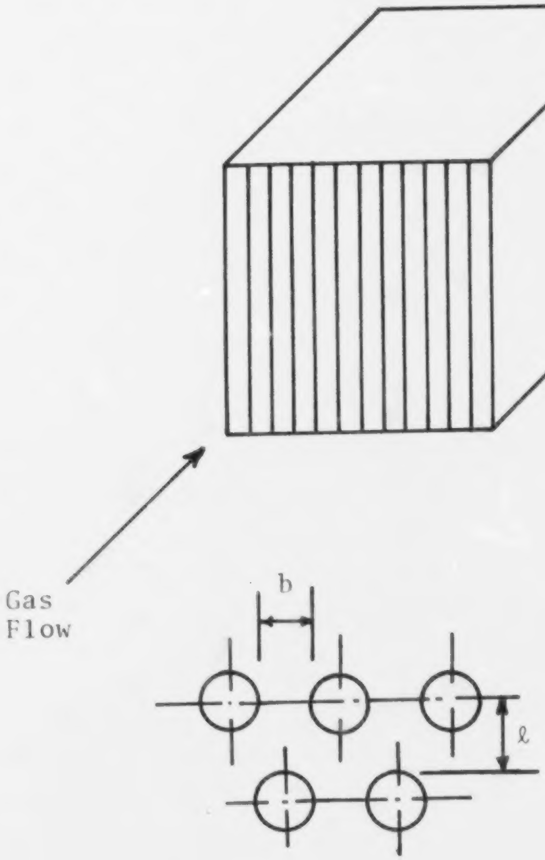


Figure 61. Sketch showing arrangement of tube bank separator.

UNCONVENTIONAL SCRUBBER COSTS

Introduction

Cost estimates for the open, unconventional scrubber are made using the same procedure previously described for the conventional scrubber. The procedure follows that of Guthrie (1970) which uses the sum of the individual module costs.

The cost modules are biased to the specific location of the test area at AFRPL's Haystack Butte and the design for the large rocket. The cost modules concerning the transition piece, the scrubber excavation, and the scrubber excavation retaining walls, etc. would be different than presented for other locations. The costs for smaller thrust rockets are based on a scale-down from the large, 2 meganewton thrust, rocket. The emphasis has been placed on the larger rockets because the cost benefit over the conventional design is much greater for the larger sizes.

Equipment Costs

Fundamental to the module approach to cost estimating is a knowledge of the equipment FOB cost or, in the case of field erected items, the total direct labor and material costs. These were taken in most part from the literature. In some instances vendor quotes were solicited to either confirm the published data or to obtain updated figures.

The 2.0 meganewton rocket size was chosen as the basis from which to scale all other rocket sizes. Scaling was performed in most cases by using literature cost exponents. The exceptions are noted in the text which follows.

Figures 62 through 70 present the costs for the individual process components listed in Table 23. The data have been presented on a cost versus rocket thrust format to simplify the total cost estimating job. Note that the figures are for total installed costs. These include all equipment costs, direct material and labor costs required for field installation and project indirects. Each of these separate items may be obtained by applying the cost factors noted on the graphs. The total project costs may be estimated by summing the module costs and adding figures for the contingency and fee. A figure of 18% has been recommended by Guthrie (1970) for this purpose.

TABLE 23. LIST OF COMPONENTS MAKING UP THE TOTAL UNCONVENTIONAL SCRUBBING PROCESS - LARGE ROCKETS

Transition piece
Scrubbing liquor viaduct and manifold
Scrubber exvacation, retaining wall deflectors
    and drag elements
Entrainment separator
Water storage tank *
Caustic storage tank *
Drainage sewer *
Drying bed *

* Common to both conventional and unconventional scrubbers.

The following summarizes the derivation of the data presented in Figures 62 through 70 . The cost basis for some items has previously been presented and are not repeated.

A) Transition Piece and Separator Costs, figures 62 and 65. Costs for the transition piece and separator were based on assuming field assembly of shop prefabricated units. Shop costs were based on material weight and fabrication manpower as presented in Calvert, et al. (1972). Cost exponent, labor, and material factors were taken from Guthrie's "norm" for chemical process modules. Indirects were taken at Guthrie's "norm" of 0.34 for the transition piece and separator. The indirect factor for the scrubber was taken at 0.60 to allow for the non-conventional nature of this item.

B) Scrubber Excavation - figure 63.

Scrubber excavation costs were taken from Lee Saylor (1976). The figures include costs for grading, leveling, and backfill. It was assumed 20% of the excavation would require blasting with the remainder requiring air tool. Indirects were taken at 0.34.

C) Scrubber Excavation Retaining Walls, Gunite, Drag and Deflector Units, figure 64.

Figure 64 presents the combined costs for the miscellaneous items making up the excavated scrubber body. Gunite is used on the excavated rock portion of the scrubber. Essentially this is confined to the wall on the uphill side of the scrubber and the base. Costs were based on information taken from Lee Saylor (1976). The purpose of the retaining wall is to make up that part of the scrubber walls not formed by the excavation. In most part, this is confined to the downhill side of the excavation. The wall supports to some extent act as drag and deflector units. Since their costing procedure was similar to that for the retaining wall, their costs were lumped together. Material costs were based on cement material quotes from vendors. Total material and labor were taken at five times the material cost in constrast to the normal 3.5 to 4.0 in order to account for the unusual field conditions. Total indirects were taken at 0.34 per Guthrie's "norm".

D) Scrubbing Liquor Viaduct and Manifold, figure 66.

Costs were derived from a combined material and labor cost based on material weight as presented in Calvert, et al. (1972). Indirects were taken at 0.34 from Guthrie's "norm".

Total Installed Costs

Figure 71 presents a summation of all the cost modules as a function of rocket size. The 18% contingency and fee factor is included. The unconventional design costs are location specific because the use of the typography in the design. The conventional design is slightly location specific because of the dependence on the hilltop location for the water tank and the length of the pipeline to the test pad. Shown for comparison is the conventional scrubber costs. For the 2 meganewton (450,000 lbf) thrust rocket the cost difference is about $2.5 million.

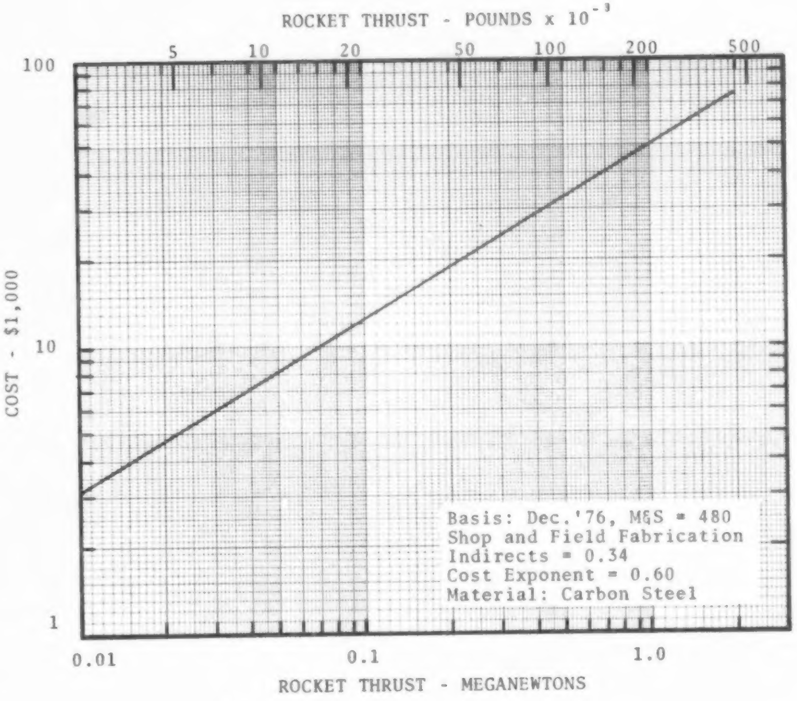
Scrubber Costs - Worked Examples

Three worked examples of cost estimates made for unconventional gas atomized scrubbers are presented in Table 24. It can readily be appreciated that the costing procedure is straightforward and needs little by way of explanation. In essence, total costs are estimated by summing the installed costs for the components listed in the table with the individual item costs taken from Figures 62 through 70. To the sum is added a percentage to allow for contingency and fee.

TABLE 24. WORKED EXAMPLES OF UNCONVENTIONAL SCRUBBER COSTS

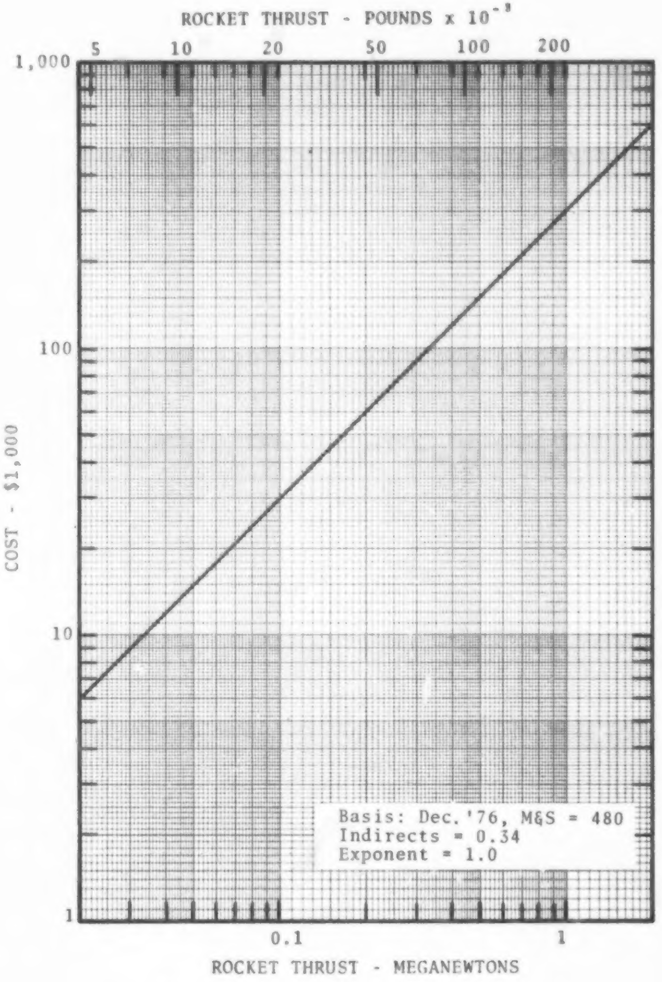
Rocket Thrust, meganewtons	2.0	0.22	0.022
Rocket Thrust, pounds-force	450,000	50,000	5,000
Cost Item		Cost $1,000	
Thrust deflector*	100	11	1
Transition piece	76	20	5
Scrubber excavation	600	66	7
Excavation retaining walls, etc.	73	24	8
Entrainment separator	220	25	2
Scrubbing liquid viaduct	88	30	10
Water storage tank	112	28	7
Caustic storage tank	23	11	5
Drainage sewer	155	27	10
Drying bed	72	8	1
Installed Cost-	$ 1,519	$ 250	$ 56
Contingency + Fee @ 18%-	273	45	10
Total Installed Cost-	$ 1,792	$ 295	$ 66

*Rough estimate



Basis: Dec.'76, M&S = 480
Shop and Field Fabrication
Indirects = 0.34
Cost Exponent = 0.60
Material: Carbon Steel

Figure 62. Transition piece costs.



Basis: Dec.'76, M&S = 480
Indirects = 0.34
Exponent = 1.0

Figure 63. Scrubber excavation costs.

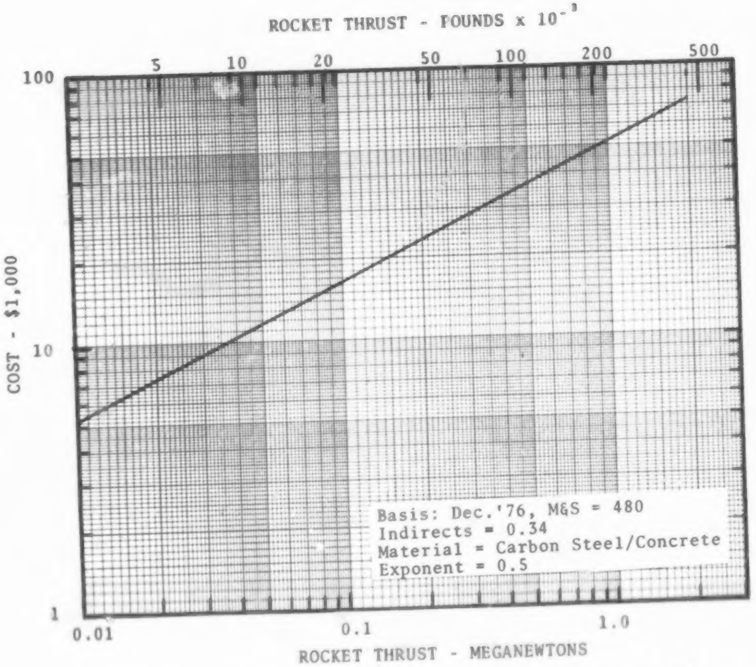


Figure 64. Costs for scrubber excavation retaining walls, gunite, drag and deflector units for large rockets.

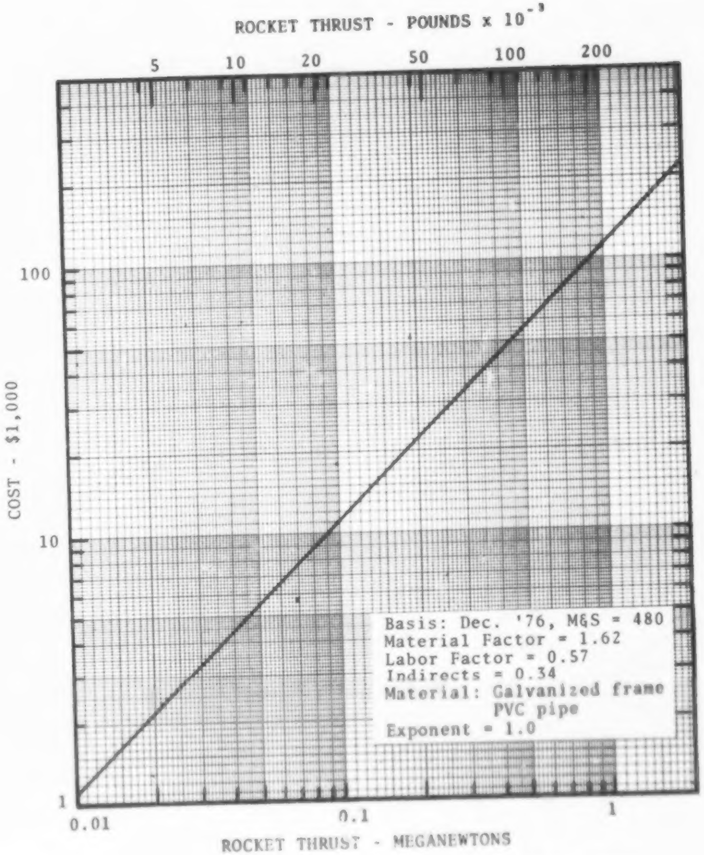


Figure 65. Entrainment separator costs.

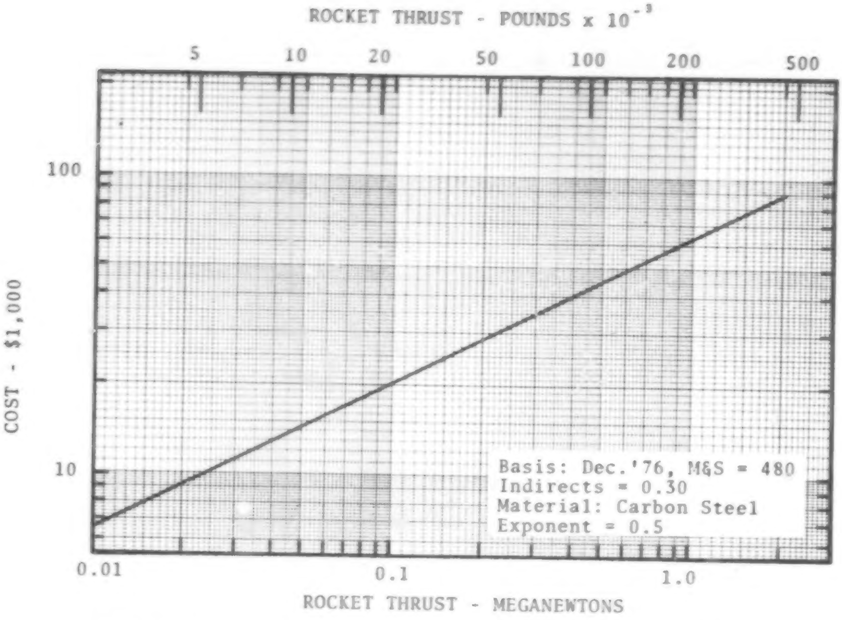


Figure 66. Scrubbing liquor viaduct and manifold costs.

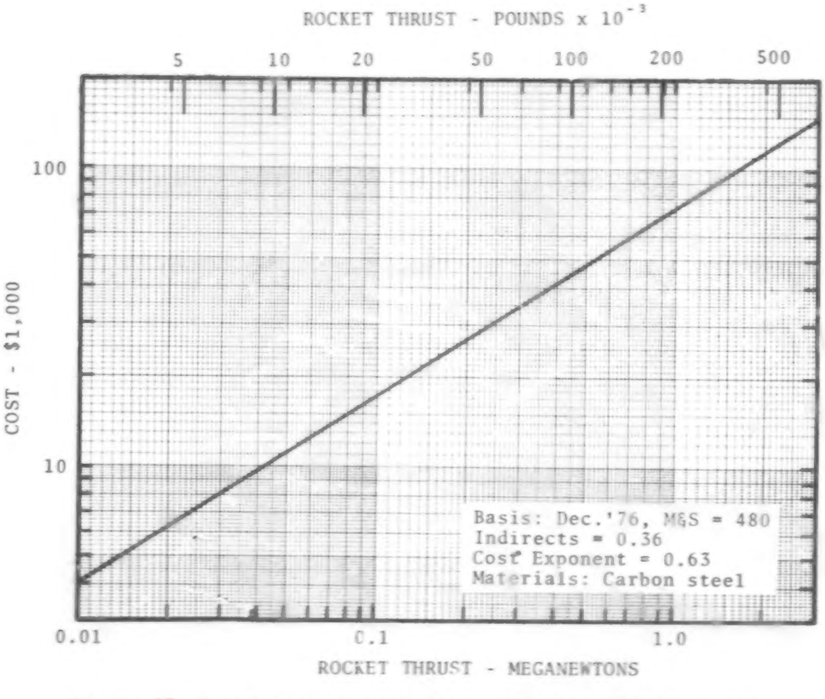


Figure 67. Water storage tank costs (figures include total materials, field installation and indirects).

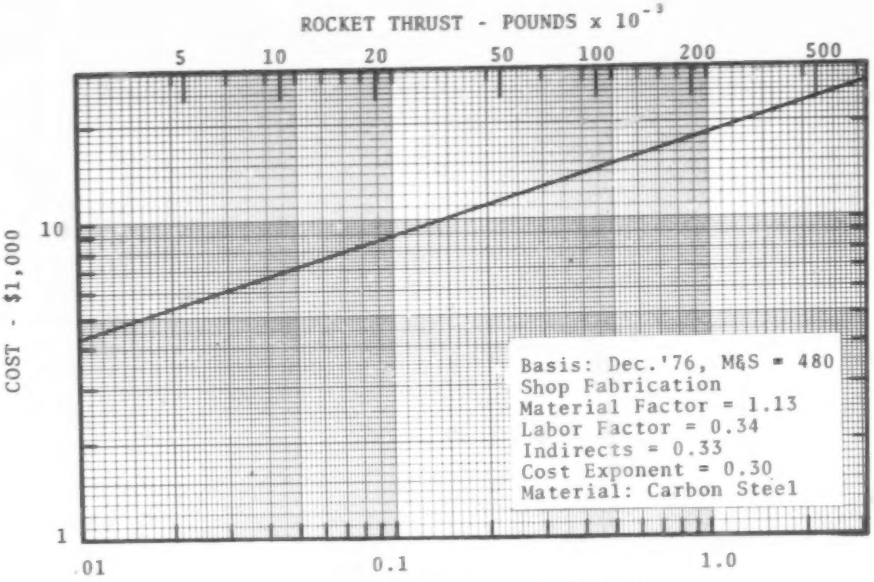


Figure 68. Caustic storage tank costs.

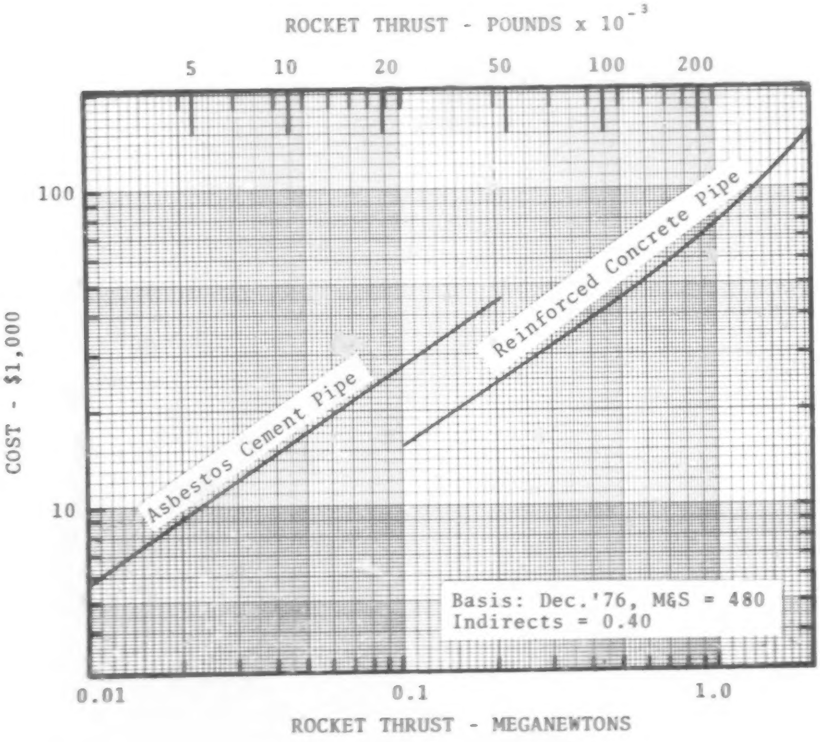


Figure 69. Drainage sewer costs.

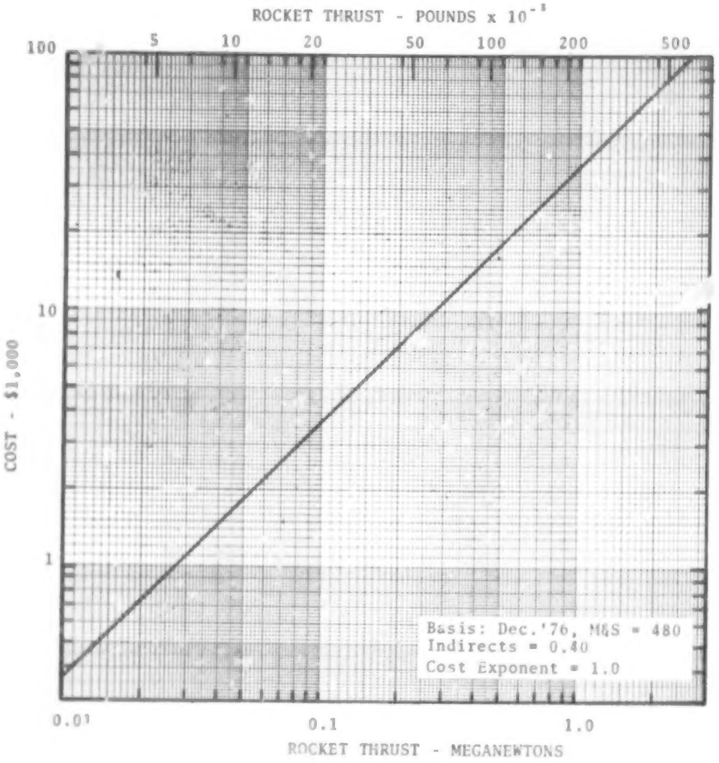


Figure 70. Drying bed costs.

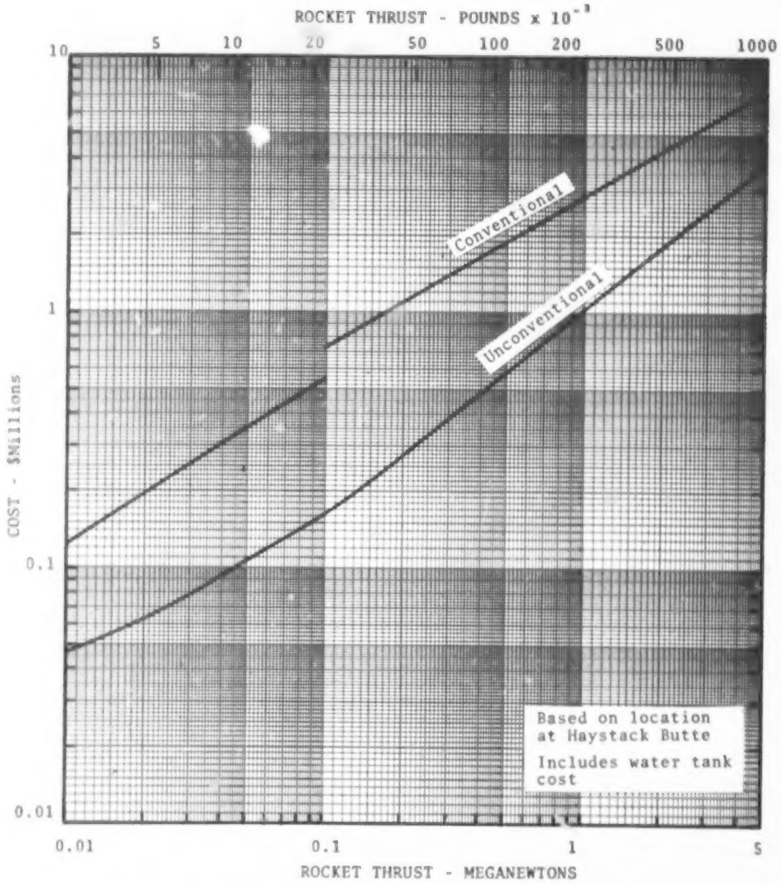


Figure 71. Total installed costs of conventional and unconventional scrubbers.

SCRUBBER OPERATION COSTS

The operation costs of the scrubber, whether the closed or open design, consist of four parts:

1. Labor
   a. Direct
   b. Supervision
   c. Overhead
2. Utilities - primarily electricity and water
3. Expended chemicals
4. Replacement parts

Labor

The detailed labor requirement for the large (450,000 lbf) thrust rocket scrubber will be considered. A test schedule of one test per month will be used. The following table (25) presents the scrubber operation plan.

TABLE 25. SCRUBBER OPERATION PLAN

Task No.	Description	Time
I.	Preparation	2 weeks preceeding run
A.	Maintain equipment	
B.	Check water flow	
C.	Mix basic solution	
D.	Fill liquid tanks	
E.	Check instrumentation	
II.	Run	Part of 1 day
III.	Clean-up	2 weeks after tun
A.	Clean out scrubber	
B.	Flush base from piping	
C.	Check drying pond	

Scrubber maintenance and operation should require a full-time operator and a part-time helper. For a large scrubber the helper may be needed about half-time. The cost of this labor for the 1 1/2 men would be about $46,800 per year using an hourly rate of $15.00 which includes supervision and overhead.

Other Costs

The utility cost would be very small since the water comes from wells and the only power is that required to drive pumps to slowly fill the water tank. The expended chemicals for 12 large rocket tests in a year would be about $25,600 per year based on Table 17.

It is difficult to estimate the cost of replacement parts for the scrubber. The possible parts that would have to be replaced would be some of the liquid injector nozzles and parts of the quencher which may be overheated.

Total Yearly Operational Costs

Based on the previous discussion the total yearly operational costs are summarized as follows for the large rocket:

Labor	$46,800
Utilities	5,000
Chemicals	25,600
Replacement Parts	10,000
Total	$87,400 per year

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

PURPOSE

The purpose of the effort described has been to design a scrubbing system for test rocket exhausts. This design was to be feasible in terms of scrubbing efficiency and cost. While the designs presented should provide for the required scrubbing efficiency at the lowest possible cost, the expense may still be too great.

DESIGN

The exhaust product of concern was gaseous hydrogen chloride, which we estimated had to be removed with 99.6% efficiency. The scrubber chosen was the gas-atomized spray of which the familiar venturi scrubber is a type. The energy required to achieve the high efficiency is supplied by the rocket exhaust. The length required for the mass transfer was determined to be about 3 meters after the exhaust had been slowed to about 100 m/s and cooled to below 100°C in a spray quencher. This mass transfer length is possible without the scrubbing liquid being basic because of the high solubility of HCl in water. The scrubbing liquid does have to be neutralized before it is released from the system, however. The amount of water required for quenching and scrubbing was about 15 times the mass flow rate of the rocket exhaust.

Early in the design effort it was determined that even this design would be expensive for large rockets. Thus, an alternative unconventional design is also proposed. It too, is a gas-atomized spray scrubber which uses the special topography available at Haystack Butte at AFRPL. To save structure costs the quench and scrubber section can be excavated from the side of the hill and left open on top. Piping costs are reduced by using open culverts which deliver the water to the top of the open scrubber. The operation and efficiency of the open gas-atomized scrubber have not been demonstrated.

An open gas-atomized scrubber can be built on flat terrain by either digging a ditch or building side walls to guide the flow. Because the scrubber operation is so intermittent, it is advantageous to use a large water storage tank and a small pump which fills the tank over a long period of time. The alternative of using a large pump which can handle the entire scrubber flow rate would involve a much greater equipment cost and the provision of a large power supply.

A major cost item of either design is the entrainment separator, which may be superfluous in some installations. The conventional design uses cyclones and the unconventional uses a tube bank. The requirement for entrainment separators must be evaluated at the time installation is considered. While they do help insure adequate mixing for complete mass transfer, if a basic scrubbing solution is used they are only removing water drops containing a salt. Thus, since the water is not being recycled and the salt laden drops may not be a pollution problem entrainment separators may not be needed.

DESIGN PROBLEMS

While the proposed designs are fairly complete there are certain aspects that require additional study. The first is the structural integrity of the entrainment separator. Mention has been made in the text of relief ports that would open when the initial blast from the rocket impacted on the air present in the system. These relief ports must operate properly or the entrainment separator will be destroyed.

A second problem is the effect on the structure of a failure of the rocket - explosion, nozzle ejection, etc. Since the rockets being tested are experimental there is more than a slight possibility of failure. Thus, provision must be made for either reducing the effects of failure in the design, or being prepared to go to the expense of rebuilding. A third problem is the design and cost of a thrust or flame deflector for rockets tested in the vertical position. The design and cost was mentioned only briefly in this report.

A final problem is the design of a "universal" scrubber. Solid rocket testing may have many purposes. Propellant and nozzle evaluation, smokeless propellant and plume studies, thrust vector control evaluation, altitude operation, and missile nosetip tests are some of the purposes. Of these few types of tests thrust vectoring presents the major problem of how to redirect the exhaust into the scrubber. Altitude testing is usually conducted in a chamber to which a scrubber could be easily made an auxiliary. Studies of the characteristics of the rocket plume will usually preclude the use of a scrubber.

AFRPL PILOT SCRUBBER

Four 10-second duration solid rocket tests were made in the 5,000 lbf (22 kN) pilot-scale rocket scrubber at AFRPL during the program. This scrubber was also a gas-atomized type, but the entrainment separator was a section of packed Tellerettes. Afterburning of hydrogen and carbon monoxide occurred at the exit of the entrainment separator, which only slightly affected the scrubber, but destroyed the gas and particulate sampling systems.

Other instrumentation and visual observations lead to the conclusion that the scrubber was greater than 99% efficient at particle (aluminum oxide) removal and probably as efficient at hydrogen chloride removal. The testing did not proceed into a series of 30-second duration tests because of the fear that the afterburning would have more serious consequences for the fiber glass entrainment separator. It was through that if the system exit had been vertical upward instead of horizontal the afterburning would have not had a noticeable effect in longer duration tests.

COSTS

The installed costs of the conventional and unconventional designs have been estimated for small and large rockets. The method used is described so that changes may easily be made as locations, situations, and costs change. The total installed cost estimates for the designs for rockets with thrusts ranging between 5,000 and 500,000 pounds (0.02-2.0 MN) are presented in Figure 71. For the 450,000 pound (2 MN) thrust rocket the conventional design installed cost was estimated to be $4.26 million and the unconventional design cost was $1.79 million (December, 1976).

The yearly operation costs for the large rocket were also estimated. Consisting of labor, utilities, chemicals, and replacement parts, the estimated yearly cost is roughly $90,000 if tests are conducted once per month.

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APPENDIX A

PROGRAMS FOR CALCULATING QUENCHER EQUIILIBRIUM

1. Closed quencher equilibrium calculation program FORTRAN IV listing
2. Closed quencher equilibrium calculation example Input/Output
3. Open quencher equilibrium calculation program FORTRAN IV listing
4. Open quencher equilibrium calculation example Input/Output

CLOSED QUENCHER EQUILIBRIUM CALCULATION PROGRAM
FORTRAN IV LISTING

```
100 ALPHA BASE(3)
110 DATA TO/298./
120 XLIN(X1,X2,Y,Y1,Y2)=X1-(X1-X2)/(Y1-Y2)*(Y1-Y)
130 TCC(P)=1668.21/(7.96681-ALØG10(P))-228.
140 ECØ(T)=6.98*T-28498.
150 EH2(T)=6.94*T-2069.
160 EØ2(T)=7.11*T-2120.
170 ECØ2(T)=9.42*T-96864.
180 EH2ØV(T)=8.1*T-60213.
190 EH2ØL(T)=18.02*T-73678.
200 EN2(T)=6.97*T-2078.
210 EHCL(T)=6.7*T+4.2E-4*T*T-24094.
220 EHF(T)=0.0*T
230 EAL(T)=21.6*T-391281.
240 INPUT,FCØ,FH2,FCØ2,FH2Ø,FN2,FHCL,FHF,FAL
250 INPUT,XMWR
260 INPUT,HCØ,HH2,HCØ2,HH2Ø,HN2,HHCL,HHF,HAL
270 INPUT,RISP,XMR,AREAE
280 INPUT,AREA2,P2
290 INPUT 49,(BASE(I),I=1,3)
295 49 FØRMAT(3A4)
300 INPUT,ATØM,HSAL1,C0,C1,C2
310 U1=RISP
320 F=RISP*XMR
330 P2A2=AREA2*P2*101325.
340 PRINT 51
350 51 FØRMAT(/,3X,19HRØCKET CØNSTITUENTS)
360 PRINT 52,FCØ,HCØ
370 52 FØRMAT(11X,1HF,9X,1HH,/,3X,2HCØ,F9.3,F10.0)
380 PRINT 53,FH2,HH2
390 53 FØRMAT(3X,2HH2,F9.3,F10.0)
400 PRINT 54,FCØ2,HCØ2
410 54 FØRMAT(3X,3HCØ2,F8.3,F10.0)
420 PRINT 55,FH2Ø,HH2Ø
430 55 FØRMAT(3X,3HH2Ø,F8.3,F10.0)
440 PRINT 56,FN2,HN2
450 56 FØRMAT(3X,2HN2,F9.3,F10.0)
460 PRINT 57,FHCL,HHCL
470 57 FØRMAT(3X,3HHCL,F8.3,F10.0)
480 PRINT 58,FHF,HHF
490 58 FØRMAT(3X,2HHF,F9.3,F10.0)
500 PRINT 59,FAL,HAL,XMWR
```

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510 59 FØRMAT(3X,4HALØX,F7.3,F10.0,/,3X,9HMØL. WT.=,F4.1)
520 PRINT 60,RISP,XMR,AREAE
530 60 FØRMAT(/,2X,11HRØCKET ISP=,F5.0,1X,3HM/S,/,
540&    9X,10HMASS RATE=,F6.2,1X,4HKG/S,/,
550&    9X,10HEXIT AREA=,F5.3,1X,2HM2)
560 PRINT 61,AREA2,P2
570 61 FØRMAT(/,2X,14HSCRUBBER AREA=,F5.2,1X,2HM2,/,
580&    2X,14HBACK PRESSURE=,F5.3,1X,3HATM)
590 P2=P2*101325.
600 PRINT 62,BASE,HSALT,C0,C1,C2
610 62 FØRMAT(/,2X,22HNEUTRALIZING AGENT IS ,3A4,/,
620&    4X,6HHFNET=,F7.0,/,4X,3HC0=,F4.2,2X,3HC1=,F7.5,2X,3HC2=,
630&    F5.3,26X)
640 AM=XMR/XMWR
650 A1=FCØ*AM
660 A2=FH2*AM
670 A4=FCØ2*AM
680 A6=FH2Ø*AM
690 A8R=FN2*AM
700 A9=FHCL*AM
710 A10=FHF*AM
720 A11=FAL*AM
730 GMS=0.0
740 HHR=A1*HCØ+A2*HH2+A4*HCØ2+A6*HH2Ø+A8R*HN2
750&    +A9*HHCL+A10*HHF+A11*HAL
760 ASALT=0.0
765 ATØN=ATØM
770 IF(ATØM.EQ.0.0) GØ TØ 20
780 ASALT=(A9+A10)/ATØM
785 IF(BASE(1).EQ."NØNE") ATØN=0.0
790 A9=0.0
800 A10=0.0
810 20 INPUT,RA
820 IF(RA.LT.0.0) STØP
830 A3=(RA*XMR)*0.21/28.97
840 A8A=A3*3.76
850 A8=A8R+A8A
860 Y3=A3-(A1+A2)/2.
870 Y3=AMAX1(0.0,Y3)
880 IF(A1.GT.A2) GØ TØ 70
890 Y1=A1-A3
900 Y1=AMAX1(0.0,Y1)
910 Y2=A1+A2+2.*(Y3-A3)-Y1
920 GØ TØ 80
930 70 Y2=A2-A3
940 Y2=AMAX1(0.0,Y2)
950 Y1=A1+A2+2.*(Y3-A3)-Y2
960 80 Y4=A1+A4-Y1
```

```
970 YG=Y1+Y2+Y3+Y4+A8+A9+A10
980 X1=Y1/YG
990 X2=Y2/YG
1000 X3=Y3/YG
1010 X4=Y4/YG
1020 XMWG=(Y1*28.01+Y2*2.016+Y3*32.+Y4*44.009+A8*28.0134+
1030&      A9*36.461+A10*20.0064)/YG
1040 PRINT 63,YG,X1,X2,X3,X4,XMWG
1050 63 FORMAT(/,2X,40HTOTAL GAS FLOW RATE W/O WATER VAPOR,NG =,
1060&    F7.3,1X,7HKGMOL/S,/,3X,5HCO/NG,2X,5HH2/NG,2X,5HO2/NG,
1070&   2X,6HCO2/NG,2X,3HMWG,/,1X,4F7.3,F7.1)
1080 PRINT 64
1090 64 FORMAT(/,3X,2HRW,4X,2HRA,4X,1HT,5X,4HPV/P,5X,1HQ,
1100&   7X,1HU,6X,2HP1,3X,6HNWL/NG,/,15X,1HC,12X,4HM3/S,
1110&   5X,3HM/S,5X,3HATM,11X)
1120 30 INPUT,RW
1130 IF(RW.LT.0.0) GO TO 20
1140 A7=RW*XMR/18.02
1150 A5=A6+A7
1160 Y5=A2+A5-Y2
1170 XM2=XMR*(1.+RW+RA)
1180 HH1=HHR+A7*EH2OL(T0)+A3*E02(T0)+A8A*EN2(T0)
1190 E1=HH1+XMR*U1*U1/8368.
1200 DO 100 I=1,199
1210 PV=P2*(1.-.005*FLOAT(I))
1220 Y6=PV*YG/(P2-PV)
1230 Y7=Y5-Y6+ATON*ASALT
1240 IF(Y7.LT.0.0) GO TO 100
1250 GMS=55.49*ASALT/Y7
1260 GMS=AMIN1(GMS,C0)
1270 APV=PV/133.322
1280 IF(ATOM.NE.0.0) APV=PV*(1.+C1*GMS**C2)/133.322
1290 TC=TCC(APV)
1300 T=TC+273.15
1310 Q2=YG*8314.*T/(P2-PV)
1320 U2=Q2/AREA2
1330 P1=(XM2*U2+P2A2-F)/(AREA2-AREAE)
1340 IF(P1.GT.P2) GO TO 100
1350 HH2=Y1*ECO(T)+Y2*EH2(T)+Y3*EO2(T)+Y4*ECO2(T)+Y6*EH2OV(T)+
1360&      Y7*EH2OL(T)+A8*EN2(T)+A9*EHCL(T)+A10*EHF(T)+A11*EAL(T)
1370&      +ASALT*HSALT
1380 E2=HH2+XM2*U2*U2/8368.
1390 PR=PV/P2
1400 IF(E2.LT.E1) GO TO 150
1410 TCP=TC
1420 PRP=PR
1430 Q2P=Q2
1440 U2P=U2
```

```
1450 P1P=P1
1460 E2P=E2
1470 Y7P=Y7
1480 GO TO 100
1490 150 TC=XLIN(TC,TCP,E1,E2,E2P)
1500 PR=XLIN(PR,PRP,E1,E2,E2P)
1510 Q2=XLIN(Q2,Q2P,E1,E2,E2P)
1520 U2=XLIN(U2,U2P,E1,E2,E2P)
1530 P1=XLIN(P1,P1P,E1,E2,E2P)
1540 Y7=XLIN(Y7,Y7P,E1,E2,E2P)
1550 P1=P1/101325.
1560 WLNG=Y7/YG
1570 PRINT 65,RW,RA,TC,PR,Q2,U2,P1,WLNG
1580 GO TO 30
1590 100 CONTINUE
1600 65 FORMAT(F6.1,F5.1,F7.1,F7.3,F9.2,F7.1,F7.3,F8.2,3X)
1610 STOP
1620 END
```

CLOSED QUENCHER EQUILIBRIUM CALCULATION EXAMPLE

INPUT/OUTPUT

```
?.194,.294,.014,.126,.087,.171,0,.114
?
 29.2
?
 -9365,15993,-66380,-35426,16886,-5560,0,-319630
?
 2590.,772.2,1.53

?50.,0.90
?
 HCL
?1,-17888.,9.99,.029,1.37


  ROCKET CONSTITUENTS
           F          H
  CO    0.194    -9365.
  H2    0.294    15993.
  CO2   0.014   -66380.
  H2O   0.126   -35426.
  N2    0.087    16886.
  HCL   0.171    -5560.
  HF    0.           0.
  ALOX  0.114  -319630.
  MOL. WT.=29.2

 ROCKET ISP=2590. M/S
        MASS RATE=772.20 KG/S
        EXIT AREA=1.530 M2

 SCRUBBER AREA=50.00 M2
 BACK PRESSURE=0.900 ATM

 NEUTRALIZING AGENT IS HCL
   HFNET=-17888.
   C0=9.99  C1=0.02900  C2=1.370
```

```
TOTAL GAS FLOW RATE W/O WATER VAPOR,NG = 17.121 KGMOL/S
 CO/NG  H2/NG  O2/NG  CO2/NG  MWG
 0.267  0.421  0.      0.054   17.9

 RW     RA      T      PV/P      Q         U       PI    NWL/NG
                C               M3/S      M/S     ATM

20.0   0.1    90.4   0.777   2541.12    50.8   0.690    47.07

18.0   0.1    91.2   0.800   2848.22    57.0   0.692    41.54

16.0   0.1    91.9   0.820   3170.07    63.4   0.692    35.97

14.0   0.1    92.5   0.837   3503.66    70.1   0.688    30.39

12.0   0.1    93.1   0.851   3846.67    76.9   0.680    24.80

10.0   0.1    93.6   0.864   4197.69    84.0   0.668    19.19

 8.0   0.1    94.3   0.874   4556.24    91.1   0.652    13.57

 6.0   0.1    95.5   0.883   4925.01    98.5   0.631     7.95

 4.0   0.1   102.3   0.890   5351.58   107.0   0.607     2.37

 3.0   0.1   108.5   0.885   5158.18   103.2   0.587     0.23

 3.5   0.1   108.6   0.892   5511.84   110.2   0.601     1.00
```

OPEN QUENCHER EQUILIBRIUM CALCULATION PROGRAM

FORTRAN IV LISTING

```
10 COMMON P2,ATOM,ATON,ASALT,CO,C1,C2,XM2,E1
20 COMMON Y1,Y2,Y3,Y4,Y5,Y6,A8,A9,A10,A11
30 COMMON RA,RW,HSALT,XMWG
40 DIMENSION ADI(10),CDI(10),RWI(10)
50 ALPHA BASE(3)
60 DATA TO/298./
90 ECO(T)=6.98*T-28498.
100 EH2(T)=6.94*T-2069.
110 EO2(T)=7.11*T-2120.
120 ECO2(T)=9.42*T-96864.
130 EH2OV(T)=8.1*T-60213.
140 EH2OL(T)=18.02*T-73678.
150 EN2(T)=6.97*T-2078.
160 EHCL(T)=6.7*T+4.2E-4*T*T-24094.
170 EHF(T)=0.0*T
180 EAL(T)=21.6*T-39128.
190 INPUT,FCO,FH2,FCO2,FH2O,FN2,FHCL,FHF,FAL
200 INPUT,XMWR
210 INPUT,HCO,HH2,HCO2,HH2O,HN2,HHCL,HHF,HAL
220 INPUT,RISP,XMR,P2,AE
230 INPUT 49,(BASE(I),I=1,3)
240 49 FORMAT(3A4)
250 INPUT,ATOM,HSALT,CO,C1,C2
260 INPUT,NB
270 INPUT,(ADI(I),I=1,NB)
280 INPUT,(CDI(I),I=1,NB)
290 INPUT,(RWI(I),I=1,NB)
300 U1=RISP
310 F=RISP*XMR
320 PRINT 51
330 51 FORMAT(/,3X,19HROCKET CONSTITUENTS)
340 PRINT 52,FCO,HCO
350 52 FORMAT(11X,1HF,9X,1HH,/,3X,2HCO,F9.3,F10.0)
360 PRINT 53,FH2,HH2
370 53 FORMAT(3X,2HH2,F9.3,F10.0)
380 PRINT 54,FCO2,HCO2
390 54 FORMAT(3X,3HCO2,F8.3,F10.0)
400 PRINT 55,FH2O,HH2O
410 55 FORMAT(3X,3HH2O,F8.3,F10.0)
420 PRINT 56,FN2,HN2
430 56 FORMAT(3X,2HN2,F9.3,F10.0)
440 PRINT 57,FHCL,HHCL
```

```
450 57 FORMAT(3X,3HHCL,F8.3,F10.0)
460 PRINT 58,FHF,HHF
470 58 FORMAT(3X,2HHF,F9.3,F10.0)
480 PRINT 59,FAL,HAL,XMWR
490 59 FORMAT(3X,4HALOX,F7.3,F10.0,/,3X,9HMOL. WT.=,F4.1)
500 PRINT 60,RISP,XMR,P2,AE
510 60 FORMAT(/,2X,11HROCKET ISP=,F5.0,1X,3HM/S,/,
520&    9X,10HMASS RATE=,F6.2,1X,4HKG/S,/,
530&    9X,9HPRESSURE=,F5.3,1X,3HATM,/,9X,13HEXHAUST AREA=,
540&    F5.3,1X,2HM2)
550 P2=P2*101325.
560 PRINT 62,BASE,HSALT,C0,C1,C2
570 62 FORMAT(/,2X,22HNEUTRALIZING AGENT IS ,3A4,/,
580&    4X,6HHFNET=,F7.0,/,4X,3HC0=,F4.2,2X,3HC1=,F7.5,2X,3HC2=,
590&    F5.3)
600 PRINT 66,NB
610 66 FORMAT(/,2X,18HNUMBER OF BAFFLES=,I2)
620 PRINT 67,(ADI(I),I=1,NB)
630 67 FORMAT(4X,14HDRAG AREAS, M2,/,4X,10F6.2)
640 PRINT 68,(CDI(I),I=1,NB)
650 68 FORMAT(4X,10HDRAG COEFS,/,4X,10F6.3)
660 PRINT 69,(RWI(I),I=1,NB)
670 69 FORMAT(4X,12HWATER RATIOS,/,4X,10F6.2)
680 AM=XMR/XMWR
690 A1=FCO*AM
700 A2=FH2*AM
710 A4=FCO2*AM
720 A6=FH2O*AM
730 A8R=FN2*AM
740 A9=FHCL*AM
750 A10=FHF*AM
760 A11=FAL*AM
770 HHR=A1*HCO+A2*HH2+A4*HCO2+A6*HH2O+A8R*HN2
780&    +A9*HHCL+A10*HHF+A11*HAL
790 ASALT=0.0
800 ATON=ATOM
810 B=F
820 IF(ATOM.EQ.0.0) GO TO 20
830 ASALT=(A9+A10)/ATOM
840 IF(BASE(1).EQ."NONE") ATON=0.0
850 A9=0.0
860 A10=0.0
870 20 INPUT,RA
880 IF(RA.LT.0.0) STOP
890 A3=(RA*XMR)*0.21/28.97
900 A8A=A3*3.76
910 A8=A8R+A8A
920 Y3=A3-(A1+A2)/2.
```

```
930 Y3=AMAX1(0.0,Y3)
940 IF(A1.GT.A2) GO TO 70
950 Y1=A1-A3
960 Y1=AMAX1(0.0,Y1)
970 Y2=A1+A2+2.*(Y3-A3)-Y1
980 GO TO 80
990 70 Y2=A2-A3
1000 Y2=AMAX1(0.0,Y2)
1010 Y1=A1+A2+2.*(Y3-A3)-Y2
1020 80 Y4=A1+A4-Y1
1030 YG=Y1+Y2+Y3+Y4+A8+A9+A10
1040 X1=Y1/YG
1050 X2=Y2/YG
1060 X3=Y3/YG
1070 X4=Y4/YG
1080 XMWG=(Y1*28.01+Y2*2.016+Y3*32.+Y4*44.009+A8*28.0134+
1090&      A9*36.461+A10*20.0064)/YG
1100 FD=0.0
1110 PRINT 63,YG,X1,X2,X3,X4,XMWG
1120 63 FORMAT(/,2X,40HTOTAL GAS FLOW RATE W/O WATER VAPOR,NG =,
1130&    F7.3,1X,7HKGMOL/S,/,3X,5HCO/NG,2X,5HH2/NG,2X,5HO2/NG,
1140&  2X,6HCO2/NG,2X,3HMWG,/,1X,4F7.3,F7.1)
1150 PRINT 64
1160 64 FORMAT(/,3X,2HRW,4X,2HRA,4X,1HT,5X,4HPV/P,5X,1HQ,
1170&  7X,1HU,6X,2HA2,3X,5HRHOGV,3X,3HMOM,/,15X,1HC,12X,4HM3/S,
1180&  5X,3HM/S,5X,2HM2,3X,5HKG/M3,4X,1HN)
1190 RW=0.0
1200 DO 200 J=1,NB
1210 AD=ADI(J)
1220 CD=CDI(J)
1230 RW=RW+RWI(J)
1240 B=B-FD
1250 A7=RW*XMR/18.02
1260 A5=A6+A7
1270 Y5=A2+A5-Y2
1280 XM2=XMR*(1.+RW+RA)
1290 HH1=HHR+A7*EH2OL(TO)+A3*EO2(10)+A8A*EN2(10)
1300 E1=HH1+XMR*U1*U1/8368.
1310 IF(RWI(J).EQ.0.0) GO TO 150
1320 CALL CALC(B,RHOGV,U2)
1330 150 CONTINUE
1340 FD=0.0
1350 IF(AD.EQ.0.0) GO TO 200
1360 FD=CD*AD*RHOGV*U2*U2/2.
1370 BD=B-FD
1380 CALL CALC(BD,RHOGV,U2)
1390 200 CONTINUE
1400 STOP
```

```
1410 END
1420 SUBROUTINE CALC(B,RHOGV,U2)
1430 COMMON P2,ATOM,ATON,ASALT,CO,C1,C2,XM2,E1
1440 COMMON Y1,Y2,Y3,Y4,Y5,YG,A8,A9,A10,A11
1450 COMMON RA,RW,HSALT,XMWG
1460 XLIN(X1,X2,Y,Y1,Y2)=X1-(X1-X2)/(Y1-Y2)*(Y1-Y)
1470 TCC(P)=1668.21/(7.96681-ALOG10(P))-228.
1480 ECO(T)=6.98*T-28498.
1490 EH2(T)=6.94*T-2069.
1500 EO2(T)=7.11*T-2120.
1510 ECO2(T)=9.42*T-96864.
1520 EH2OV(T)=8.1*T-60213.
1530 EH2OL(T)=18.02*T-73678.
1540 EN2(T)=6.97*T-2078.
1550 EHCL(T)=6.7*T+4.2E-4*T*T-24094.
1560 EHF(T)=0.0*T
1570 EAL(T)=21.6*T- 391281
1580 GMS=0.0
1585 U2=B/XM2
1590 DO 100 I=1,199
1600 PV=P2*(1.-.005*FLOAT(I))
1610 Y6=PV*YG/(P2-PV)
1620 Y7=Y5-Y6+ATON*ASALT
1630 IF(Y7.LT.0.0) GO TO 100
1640 GMS=55.49*ASALT/Y7
1650 GMS=AMIN1(GMS,CO)
1660 APV=PV/133.322
1670 IF(ATOM.NE.0.0) APV=PV*(1.+C1*GMS**C2)/133.322
1680 TC=TCC(APV)
1690 T=TC+273.15
1700 Q2=YG*8314.*T/(P2-PV)
1750 HH2=Y1*ECO(T)+Y2*EH2(T)+Y3*EO2(T)+Y4*ECO2(T)+Y6*EH2OV(T)+
1760&     Y7*EH2OL(T)+A8*EN2(T)+A9*EHCL(T)+A10*EHF(T)+A11*EAL(T)
1770&     +ASALT*HSALT
1780 E2=HH2+XM2*U2*U2/8368.
1790 PR=PV/P2
1800 IF(E2.LT.E1) GO TO 150
1810 TCP=TC
1820 PRP=PR
1830 Q2P=Q2
1850 E2P=E2
1860 GO TO 100
1870 150 TC=XLIN(TC,TCP,E1,E2,E2P)
1880 PR=XLIN(PR,PRP,E1,E2,E2P)
1890 Q2=XLIN(Q2,Q2P,E1,E2,E2P)
1910 AREA2=Q2/U2
1930 RHOGV=YG*(18.02*PR/(1.-PR) + XMWG)/Q2
1940 PRINT 65,RW,RA,TC,PR,Q2,U2,AREA2,RHOGV,B
1950 RETURN
1960 100 CONTINUE
1970 65 FORMAT(F6.1,F5.1,F7.1,F7.3,F9.2,F7.1,F7.2,F7.3,E10.3)
1980 RETURN
1990 END
```

OPEN QUENCHER EQUILIBRIUM CALCULATION EXAMPLE

INPUT/OUTPUT

```
?.194,.294,.014,.126,.087,.171,0,.114
?
 29.2
?
 -9365,15993,-66380,-35426,16886,-5560,0,-319630
?
 2590.,772.2,0.90,1.53
?
 HCL
?
 1,-17888.,9.99,.029,1.37
?9
?0,0,0,0,0,0,0,0,0
?0,0,0,0,0,0,0,0,0
?4,2,2,2,2,2,2,2,2


  ROCKET CONSTITUENTS
           F          H
  CO     0.194     -9365.
  H2     0.294     15993.
  CO2    0.014    -66380.
  H2O    0.126    -35426.
  N2     0.087     16886.
  HCL    0.171     -5560.
  HF     0.            0.
  ALOX   0.114   -319630.
  MOL. WT.=29.2

 ROCKET ISP=2590. M/S
        MASS RATE=772.20 KG/S
        PRESSURE=0.900 ATM
        EXHAUST AREA=1.530 M2

 NEUTRALIZING AGENT IS HCL
   HFNET=-17888.
   CO=9.99  C1=0.02900  C2=1.370

 NUMBER OF BAFFLES= 9
   DRAG AREAS, M2
     0.     0.     0.     0.     0.     0.     0.     0.     0.
   DRAG COEFS
    0.     0.     0.     0.     0.     0.     0.     0.     0.
   WATER RATIOS
     4.00   2.00   2.00   2.00   2.00   2.00   2.00   2.00   2.00
```

```
TOTAL GAS FLOW RATE W/0 WATER VAPOR,NG = 17.121 KGMOL/S
 CO/NG   H2/NG   O2/NG   CO2/NG   MWG
 0.267   0.421   0.      0.054    17.9

 RW      RA       T       PV/P       Q          U        A2     RHOGV     MOM
                  C                 M3/S       M/S       M2     KG/M3      N
  4.0    0.1     99.8    0.882    4930.13    507.8     9.71    0.529 0.200E+07
  6.0    0.1     95.1    0.876    4648.17    364.8    12.74    0.536 0.200E+07
  8.0    0.1     94.1    0.868    4349.40    284.6    15.28    0.538 0.200E+07
 10.0    0.1     93.4    0.858    4034.83    233.3    17.29    0.539 0.200E+07
 12.0    0.1     92.9    0.846    3713.78    197.7    18.78    0.539 0.200E+07
 14.0    0.1     92.4    0.832    3392.30    171.5    19.78    0.540 0.200E+07
 16.0    0.1     91.8    0.815    3074.86    151.5    20.30    0.541 0.200E+07
 18.0    0.1     91.0    0.794    2765.68    135.6    20.40    0.542 0.200E+07
 20.0    0.1     90.2    0.770    2469.03    122.7    20.11    0.543 0.200E+07
```

APPENDIX B

CONVERSIONS

joule (J) x 0.2390 = calorie (cal)
joule (J) x 9.478×10^{-4} = BTU
liter (ℓ) x 0.2642 = gallon (gal)
meter (m) x 3.281 = feet (ft)
m^3 x 35.31 = ft^3
newton (N) x 0.2248 = pounds (lbf)
pascal (N/m^2) x 1.450×10^{-4} = lbf/in^2 (psi)
pascal (N/m^2) x 4.019×10^{-3} = inch water column (in. W.C.)
pascal (N/m^2) x 1.020×10^{-2} = centimeter water column (cm W.C.)
watt (W) x 1.340×10^{-3} = horsepower (HP)
watt (W) x 3.412 = BTU/hour

END
DATE
FILMED
8-11-78
NTIS